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# CALISTOGA GEOTHERMAL RESOURCE ASSESSMENT

## FINAL

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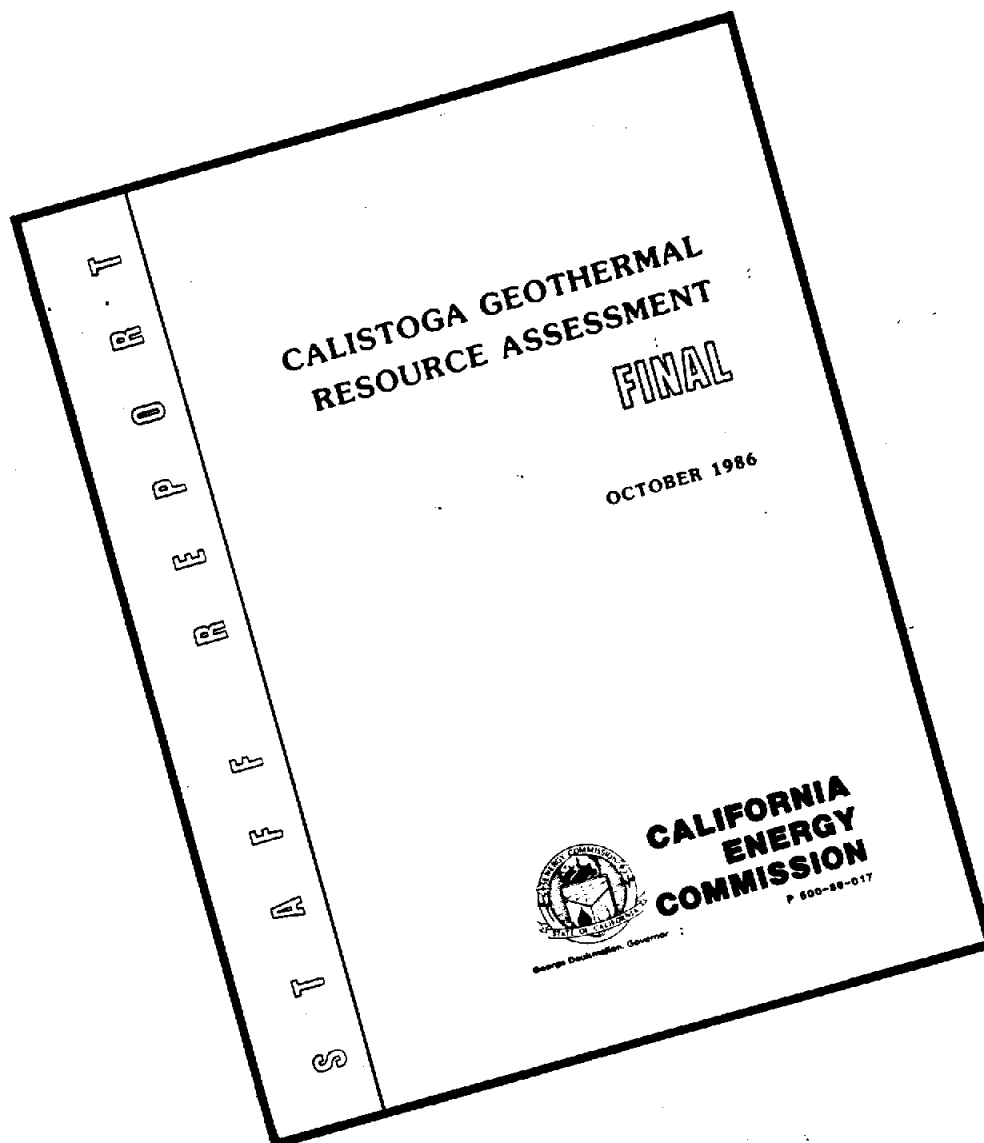


George Deukmejian, Governor

# CALIFORNIA ENERGY COMMISSION

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## I. SUMMARY OF CONTENT

The Calistoga Geothermal Field represents a shallow, moderate temperature resource located at the head of the Napa Valley, within and near the town of Calistoga. The geothermal resource is believed to be associated with a linear fault or fracture system located parallel to the axis of the Napa Valley.

The linear fracture system, which extends from Pacheteau's Spa on the southeast to the California Geyser on the northwest, channels fluids from great depth up into a shallow subsurface aquifer beneath the town of Calistoga. The upwelling thermal fluids are easily distinguished from fresh surface water by an indicative chemical signature determined from water analyses of various wells across the valley. The geothermal fluids typically display high concentrations of boron, chloride, and fluoride, and low concentrations of sulfate, iron and bicarbonate. Analyses from the overlying freshwater aquifer shows the opposite trend in the concentration of the same ions.

Samples from 140 water wells were evaluated in an attempt to determine the geographical extent and quality of the geothermal resource, the degree of mixing with surface water, the rate of recharge and the recharge temperature. In addition, a test drilling program, supplemented by geophysical work, has helped to confirm information on the thickness and subsurface of the geothermal reservoir. This information has led to the development of a fault-charged model for the Calistoga geothermal field and has allowed estimates to be made of the specific yield and energy potential of the reservoir. It is believed, on the basis of this study that, given current and projected rates of fluid withdrawal by the City, water bottlers and spas (projected rate based on the development of a district heating system utilizing 160 to 200 gpm), the resource could be expected to have a usable life of 100 years.

The primary purpose of this report, however, is to develop base-line data on which to evaluate fluctuations within the geothermal field. Through subsequent bimonthly field monitoring of water levels and chemistry, it should be possible to more accurately determine rate of fluid depletion and to suggest methods of enhancing the exploitation of the reservoir to increase reservoir longevity.

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## II. INTRODUCTION

### A. SCOPE

In September 1983, the California Energy Commission (CEC) awarded a grant to the City of Calistoga to complete a preliminary assessment of the City's geothermal resources. In addition, the grant included funds to drill a geothermal well, construct a geothermal space-heating system using a down-hole heat exchanger, and retrofit two City buildings.

In December of 1983, the City of Calistoga requested technical assistance from the CEC to initiate the task of assessing the City's geothermal resources. In accordance with this request, the CEC began a preliminary assessment of the Calistoga Geothermal field in early 1984.

The study ultimately consisted of a literature/data search and evaluation, reconnaissance geologic mapping, a geochemical survey (including both radiogenic and stable isotope analyses), a detailed hydrologic evaluation, and temperature-gradient well drilling and logging (both lithologic and temperature logging). The field work was performed in part by students from California State University in Sacramento, and the Mackay School of Mines of the University of Nevada at Reno, between May 1984 and August 1985. The results of these investigations were subsequently evaluated to arrive at a conceptual model of the Calistoga geothermal system.

Early in the course of the investigation it became evident that the Calistoga geothermal field was capable of sustaining large-scale development. At the suggestion of the CEC, the City of Calistoga in July of 1984 decided to evaluate the potential of developing a sophisticated geothermal distribution system capable of providing economical space heating to a portion of the downtown commercial business district. This decision by the City of Calistoga prompted a more detailed assessment of the Calistoga Geothermal field to insure that the resource was adequate for this type of development. It was decided that money from the current grant be used to fund the proposed assessment. The remainder of this report discusses the results of this investigation.

### B. BACKGROUND

The upper Napa Valley-Calistoga area was famous for its thermal springs long before interest in geothermal development began in The Geysers KGRA to the northwest. From the early 1860s to well into the 1920s Calistoga's mineral baths and spas were known internationally, including the Pacheteau Original Hot Springs Inc., and Nances Hot Springs. Tourism today still centers around the mud-bath spa industry. Guests at an early turn-of-the-century spa would not only bathe and steam themselves, but also drink the natural spring waters in hopes of improving their overall health. Today, bottled mineral water constitutes a thriving business in Calistoga, with three mineral water-bottling companies operating in town. A fourth, with its operations located in Santa Rosa, derives its water from the Pacheteau's wells. Together, the

spas and the bottled water industry are responsible for the withdrawal of more than 55 million gallons of water per year from the geothermal reservoir. In addition, through their lobbying efforts, they have been able to exert considerable control over further geothermal development within the City of Calistoga. Over the years, they have successfully opposed projects which had proposed to extract geothermal fluids and subsequently inject them back into the reservoir, thereby limiting large-scale geothermal development. This opposition to development by the spa owners and bottlers of mineral water was based on the inane fear that the reservoir would become depleted and/or contaminated by such projects. As a result, any proposal for large-scale geothermal development must fully evaluate the reservoir dynamics to understand resource longevity and must include an analysis of the effect of injection upon the quality of the water.

#### C. SITE DESCRIPTION

The City of Calistoga is located in the upper Napa Valley, approximately 60 miles north of San Francisco, and about 10 miles southeast of The Geysers' high-temperature KGRA. The upper Napa Valley itself is situated at the southern end of the Mayacmas Mountains, part of the Coast Range province of California. The Mountains are characterized by rugged topography with elevations up to 4,600 feet.

Climate of the Napa Valley is characterized by dry, hot summers and wet, cool winters. Mean annual rainfall at Calistoga, 360 feet above sea-level, is 36 inches, with a 10-year return annual precipitation of over 47 inches. The annual precipitation, based on 75 years of record, ranges from 12 to 70 inches. On Mount St. Helena, at an elevation of 1,792 feet above mean sea level, the mean annual precipitation is 44 inches, with a 10-year return rainfall of 63 inches in a year. Within the study area, precipitation generally follows this pattern including increased rainfall intensity and quantity with increasing topographic elevation.

In Calistoga, approximately 90 percent of annual precipitation occurs during November through April. Precipitation patterns during the rainy season are characterized by a period of stormy weather alternating with fair weather. Periods of prolonged and intensive rainfall come from cyclonic systems approaching the California coast with winds from the southwest. Because of these winds, approximately 80 percent of the precipitation in the region is accompanied by winds from a southerly direction. Summertime afternoon air temperature on the valley floor soars into the low 90s, while temperatures during winter and spring nights occasionally drop below freezing. Micrometeorological conditions resulting from variability of terrain, aspect, and relief influence both temperature and precipitation patterns within the study area. Vegetation patterns are affected by climate, elevation and soil type. Grassland, scrub oak, and stands of cypress, manzanita, and other chapparral-type plants are distributed between the valley floor and the highlands. Evergreen conifers and some deciduous plants, such as dogwood, are restricted to the higher elevations and often are indigenous to soils developed on certain rock types such as serpentinite and rhyolite.

#### D. PREVIOUS GEOTHERMAL INVESTIGATIONS

The earliest geothermal reconnaissance studies in the upper Napa Valley were accomplished by Waring (1915), who suggested that faulting was responsible for the hot water at the original hot springs of Calistoga. Regional water resource studies for the Napa Valley were completed by Bryan (1932) and Kunkel and Upson (1960). Increased utilization of groundwater for agricultural irrigation and frost protection resulted in published investigations by the U.S. Bureau of Reclamation (1966) and the Napa County Flood Control and Water Conservation District (1972). In 1973 Faye, working with the United States Geologic survey, published a comprehensive study of groundwater hydrology in the northern Napa Valley. In 1980, Youngs and others, and in 1981, Taylor and others, published reports on the geothermal resources of Calistoga for the California Department of Mines and Geology. These last two studies established a data base of water chemistry and groundwater temperatures in the Calistoga area, which provided the background for the supplemental field work and analysis for this investigation.

### III. GENERAL GEOLOGY

#### A. INTRODUCTION

The geology of the Calistoga area has been studied and mapped by Johnson (1940), Carter (1943), Weaver (1949), Taliaferro (1951), Kunkel and Upson (1960), Koenig (1961, 1963), Blake and others (1971), Fox and others (1973), Youngs and others (1980), Taylor and others (1981) and Fox (1983). Geologic reconnaissance for this investigation was completed to determine more accurately the characteristics of the geothermal system and to assist in the design of the geochemical, hydrologic and drilling programs. The brief description of the regional and site geology summarized below has thus been largely abstracted from published works.

The City of Calistoga lies within the southern end of the Mayacmas Mountains, which are characterized by a series of northwest-trending folded and faulted blocks and thrust plates (Fig. 1). The mountains are thus typically broken into a corresponding series of northwest-trending ridges and valleys.

Within the Mayacmas Mountains, the Great Valley Sequence of Jurassic to Cretaceous marine miogeosynclinal sedimentary rocks and underlying igneous rocks are in thrust fault contact with and overlie the rocks of the eugeosynclinal Franciscan assemblage of similar age. Also present in this zone are: Marine sedimentary rocks of Tertiary age, southeast of Clear Lake; the Sonoma Volcanics, of Pliocene age, near and south of Mount St. Helena; and numerous scattered exposures of non-marine sedimentary rocks of Pliocene to Holocene age.

#### B. PRE-TERTIARY ROCK SEQUENCES

The Mayacmas Mountains of northern California consist in part of two essentially coeval units separated by a large regional fault system, frequently referred to as Coast Range Thrust (Bailey and others, 1970). The upper plate consists of a sequence of ultramafic rocks, interpreted to be a fragmented ophiolite complex of Late Jurassic age (McLaughlin and Donnelly, 1981), overlain by moderately deformed marine sedimentary rocks referred to as the Great Valley Sequence (Bailey and others, 1964). The Great Valley Sequence, ranging in age from Late Jurassic to Late Cretaceous consists of ophiolitic breccia, conglomerate, mudstone and sandstone. This sedimentary sequence has been interpreted to represent Klamath- or Sierran-derived arc-trench gap or fore-arc basin deposits (Dickerson, 1970; Ingersoll and others, 1977).

Rocks in the lower plate of the Coast Range thrust have been assigned to the Franciscan assemblage and consist of a heterogeneous assemblage of intensely deformed and slightly-to-moderately metamorphosed sandstone, shale, chert, and mafic igneous rocks (McLaughlin and Donnelly, 1981). Serpentinite, limestone, amphibolite, eclogite, and high grade blueschist are minor but important constituents. Initial deformation and metamorphism appear to have occurred in the Cretaceous and early Tertiary periods, possibly as a result of northeast-directed subduction.

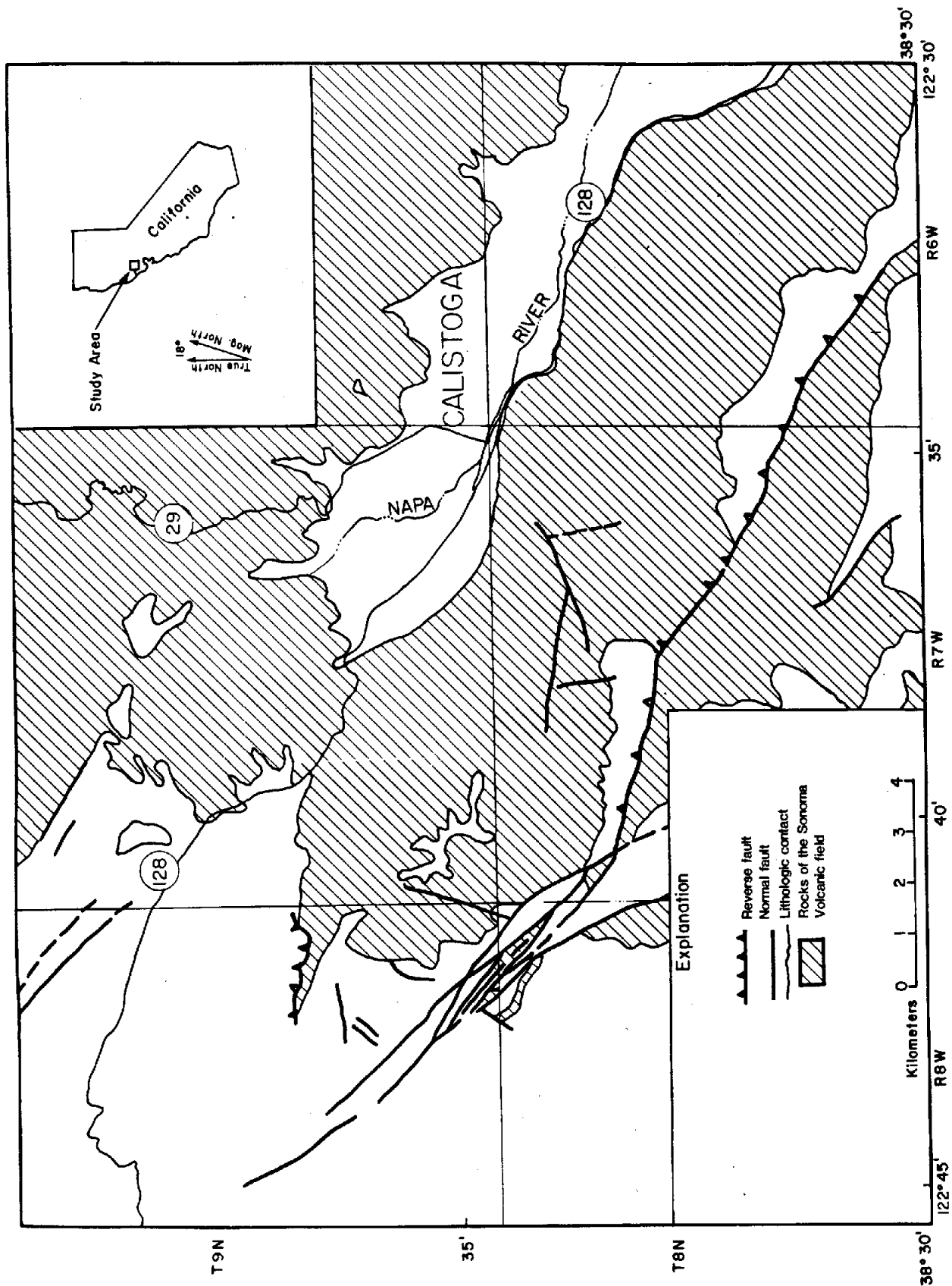


Figure 1. Generalized Geologic Map of the Upper Napa Valley Region.

The Franciscan assemblage has been largely interpreted as being deposited in a trench over an east-dipping subduction zone located west of the fore-arc basin of the Great Valley Sequence. Recent Paleomagnetic evidence, however (Jones and others, 1977; Alvarez and others, 1979), has suggested that as much as 30° of northward translation may have occurred along the Pacific margin in pre-Late Cretaceous time, with perhaps an additional 56-57° of late Cretaceous or younger northward translation. The resulting implication is that oblique northeast-directed subduction may have initiated strike-slip movement which resulted in large-scale northward displacement of the Franciscan assemblage and possibly even the Great Valley Sequence from their original sites of deposition before, during or after periods of pre-Late Cretaceous subduction (McLaughlin and Donnelly, 1981).

### C. SONOMA VOLCANICS

Tertiary volcanic rocks are exposed on the surface around the margins of the Napa Valley. These rocks generally range in age from 2.9 to 5.3 my and are considered to constitute a part of the Sonoma Volcanics of upper Pliocene age.

It is popularly believed that the emplacement of magma into the crust beneath the Calistoga area is tied closely to passage of the Mendocino triple junction and crustal extension within the northward propagating San Andreas fault system (McLaughlin, 1977; Donnelly, 1977; Hearn and others, 1981). North to northeast-oriented normal faults associated with right-angle shears within the San Andreas system apparently acted as conduits for venting of the Sonoma and younger Clear Lake magmas to the north. Magma sources for the region are highly speculative, but isotope studies (Hearn and others, 1981) have suggested that the lavas are derived in part from primitive mantle material that underwent considerable mixing, fractional crystallization and assimilation during emplacement into the crust.

The resulting Sonoma volcanics constitute a thick and highly variable series of volcanic rocks including andesite, basalt, and minor rhyolite flows with interbedded and discontinuous layers of tuff, tuff breccia, agglomerate and scoria.

Tuff, by far the most common and widely distributed rock in the Sonoma Volcanics, is a fragmental rock made up entirely of volcanic material. Enormous quantities of volcanic ash were showered on the area and accumulated under various conditions. Most of these tuffaceous rocks appear to be massive and were deposited on the irregular surface of the land. Locally, however, some of them are definitely water-lain, apparently as shallow lake deposits. Tuff formed in this manner is often soft, and usually fine-grained and light, both in color and weight. Coarse varieties are common, however, and, in some places, these appear to be more typically agglomeratic, containing angular particles of andesite and basalt. Ordinarily, the massive tuff contains numerous pumice fragments which vary in size from very small grains to fragments up to an inch or more in length. The majority of the tuff is white in color, but gray and buff-colored varieties are common, and in some localities the gray and white tuffs occur interbedded (Johnston, 1948).

The tuffs are separated at a number of horizons by lava flows, which are either basaltic or andesitic in composition. These lavas usually occur as dense, heavy, very fine-grained rocks, but are commonly scoriaceous, have vesicles which may or may not be filled, and may be porphyritic in nature. Flow banding is commonly present and columnar jointing occurs locally. The lava flows are much more resistant to weathering and erosion than the tuffs, and they usually crop out in steep cliffs and form caps on many of the ridges.

A number of lenses of sediments, composed almost entirely of thinly-bedded volcanic material, are found locally. These sediments are composed of loosely consolidated sands, gravels, and conglomerates, most of which were probably deposited in streams or shallow lakes during erosional intervals between periods of volcanism.

Reworked pyroclastic material, diatomite, silt, sand and gravel are exposed in roadcuts along the Silverado Trail east and southeast of St. Helena. In the vicinity of Calistoga, prominent bodies of rhyolite and rhyolitic tuff have been altered by hydrothermal processes to a hard, dense, fine-grained rock. Thin-section and x-ray diffraction analyses indicate that the altered rhyolitic rocks now consist primarily of quartz and kaolinitic and montmorillonitic clays (Youngs and others, 1980).

#### D. ALLUVIUM

In this report, deposits described as alluvium include the older alluvium, terrace deposits, older alluvial-fan deposits, and younger alluvium as mapped and described by Kunkel and Upson (1960) and Fox (1983).

The older alluvium of Napa Valley is composed of lenticular deposits of unconsolidated and poorly-sorted clay, silt, sand, and gravel. Where exposed at the surface, the alluvium is predominantly a reddish-brown color and exhibits cross-bedding. The material is unconsolidated but somewhat compacted, and some lenses of gravel are cemented. The sand and gravel fragments are composed mainly of andesitic debris but also include chert.

Terrace deposits include numerous isolated bodies of unconsolidated clay, sand, gravel, and cobbles that cap hilltops and benches or border the base of steep hills and mountain slopes. All these bodies are thin and of small extent. Locally, they conceal the older formations on which they lie unconformably. Some are remnants of former river channel or flood-plain deposits, some may be marine terrace deposits, and some are older alluvial fan deposits. They occur at several altitudes above present sea level and present stream grades. They range in thickness from 0 to 15 feet, except for the older alluvial fan deposits which may be considerably thicker. No fossils have been found in these unconsolidated deposits, but their stratigraphic position indicates an age from late Pleistocene to late Holocene. They may be equivalent in part to the older alluvium. Although in most places they contain a large proportion of sand and gravel, the deposits are typically

non-waterbearing since they are generally thin and occur above the water table. Where these deposits overlie either the Huichica or the Glen Ellen formations, the coarse gravel of the terrace deposits may easily be mistaken for gravel interbedded with the underlying formations, and a false impression of the water-bearing character of the underlying formations may be inferred (Youngs and others, 1980). Because these deposits are mainly non-water bearing, they have been mapped only where they are relatively thick or where they obscure the nature of the underlying formations (Kunkel and Upson, 1960).

The younger alluvium consists of interbedded, unconsolidated gravel, sand, silt, clay, and peat in beds comprising channel, flood plain, and alluvial fan deposits. These deposits overlie or overlap all other formations in the Napa Valley. They were deposited by modern streams, but in valleys that were once cut to a lower position of sea level, corresponding to a late Pleistocene glacial stage (Upson, 1949; Louderback, 1951). Hence, the younger alluvium may be in part late Pleistocene, but is typically considered to be Holocene (recent), because deposition is continuing today (Kunkel and Upson, 1960).

The floor of the Napa Valley consists of channel deposits and flood-plain deposits composed predominantly of well-sorted gravels and sand interbedded with silts. This material is not well-exposed in section, and for the most part is indistinguishable from the older alluvium. However, these deposits are typically less than 30 feet thick.

#### E. GEOLOGIC STRUCTURE

The geologic structure for much of the Mayacmas Mountains area is characterized by the northwest trends of the Jurassic and Cretaceous rock sequences and the fault zones that separate them into tilted and folded blocks of strata. The area north of Calistoga is essentially bisected by a major thrust zone, the Soda Creek thrust of Swe and Dickinson (1970). This zone, which apparently follows a discontinuous line of northwest-trending serpentinite outcrops, marks the line of separation between the outcrop areas of the Great Valley Sequence on the northeast and the Franciscan assemblage on the southwest.

Swe and Dickinson (1970) have suggested that the Great Valley Sequence, together with Eocene and Paleocene strata, form a thrust complex that rests structurally upon the Franciscan assemblage along the Soda Creek fault. The Great Valley Sequence is then in turn overlain unconformably by late Cenozoic strata. A number of subsidiary thrusts, that are discordant to the bedding, divide both the Great Valley Sequence and the Franciscan assemblage into three or more successive thrust plates or slices (McLaughlin and Donnelly, 1981).

Emplacement by regional thrust faulting of the Great Valley Sequence and early Tertiary rocks above the Franciscan assemblage was probably complete by Oligocene time, after which the entire complex, including the thrust faults themselves, were folded and cut by faulting during later Cenozoic deformations. The late Tertiary-early Quaternary orogeny, which probably produced most of this folding and faulting, also

brought with it the volcanism that produced the Sonoma Volcanics and the Clear Lake lavas. Mount St. Helena itself is built up of a series of folded flows and beds and is not a former major volcanic vent (Youngs and others, 1980). The fact that the maximum dip of beds in the vicinity does not usually exceed  $20^\circ$  indicates that orogenic activity in that area was relatively mild in post-Sonoma Volcanics time.

Folding and erosion have exposed the Soda Creek thrust and underlying Franciscan rocks along the Soda Creek anticline outside the Calistoga area on the north. Of the several subsidiary thrust or other faults known to have sizable displacements within the Great Valley Sequence, most prominent is the Collayomi fault. This fault may be associated with the Soda Creek thrust which divides the Great Valley and Franciscan rocks.

The more important fault zones associated with the Franciscan assemblage outcrop area include (1) the complex fault zone along Big Sulphur Creek to the northwest; (2) the Little Sulphur fault and Black Mountain fault zone that bound the Little Sulphur graben along Little Sulphur Creek; and (3) the Maacama and Chianti fault zones. Gealey (1951) estimates that the Sonoma volcanic rocks have been downdropped by nearly 2,100 feet (700 m) by the combined action along the Maacama and adjacent Chianti fault zones that border the Mayacmas Mountains on the southwest. These facts would tend to agree, at least in part, with the concept expressed by McNitt (1968) that the Mayacmas Mountains are a large complex horst bounded by faults.

#### Local Folding

As mentioned above, the folding that has affected the Franciscan rocks is difficult to document in the Calistoga area due to lack of outcrops and reliable attitudes. That folding and faulting have occurred in the Franciscan rocks is evidenced by sharp attitude changes within short distances and near-vertical to vertical bedding.

The rocks of the Sonoma Volcanics that cover most of the Franciscan rocks south of Mt. St. Helena were gently folded and faulted by compressional forces from the northeast or southwest after their deposition. Broad, parallel synclines and anticlines transgress the area in a northwest-southeast direction and, in general, the topography follows these folds. Thus, Napa Valley is a broad, asymmetric syncline plunging to the southeast, and the large mass of overthrust Franciscan rocks exposed to the southwest of Napa Valley comprises the crest of an anticline. Gentle dips in the range of  $10^\circ$  to  $30^\circ$  are the most common within the Sonoma Volcanics, although steep dips and tight folds have been documented (Johnston, 1948, p. 32).

#### Local Faulting

The pre-Pliocene (pre-Sonoma Volcanics) faults that occur within the Franciscan assemblage, although contemporaneous with major folding, are poorly exposed within the study area. Major northwest trending fault zones in Franciscan rocks have been mapped to the northwest of Napa Valley (Fox, 1983), but the overlying Tertiary volcanic rocks and Quaternary alluvium mask any pre-Sonoma faulting that may be present within the Napa Valley.

The Sonoma Volcanics show some evidence of Pliocene and post-Pliocene faulting. Mapping by Fox (1983) has shown the occurrence of two relatively short faults north of the town of Calistoga, as well as some relatively large, both in length and possible displacement, faults occurring 3 to 5 miles south and southeast of Calistoga. The faults all appear to be of normal displacement.

A major structural feature with a strong local effect is the large northwest trending thrust; along which Franciscan rocks have been overthrust upon Sonoma Volcanic rocks at a relatively shallow angle of  $20^{\circ}$  to  $30^{\circ}$ . This thrust is the major feature of the western limb of the Napa Valley syncline. The eastern terminus of this thrust, in all probability, is coincident with the current axial plane of the Napa Valley and may result in a major structural discontinuity underlying the Napa Valley.

#### IV. HYDROLOGY

##### A. INTRODUCTION

The purpose of the hydrology section of this study is to aid in the formulation of an accurate conceptual model of the Calistoga Geothermal field and to provide a data base for future studies. Preliminary efforts have been devoted to potentiometric surface measurements, along with hydrochemical analysis, for interpretation of aquifer dynamics. General objectives are the determination of flow patterns, zones of mixing, and seasonal variation. Analysis correlating hydrothermal anomalies with water chemistry will provide indications of zones for potential high-temperature geothermal utilization. Most of the work will be focused in the area of the Calistoga geothermal anomaly.

Specific tasks completed for the hydrologic section of this study are as follows:

- (1) Review available hydrologic and hydrochemical literature,
- (2) Obtain and analyze water samples from selected wells and springs for major/minor ion chemistry,
- (3) Collect temperature data from selected wells and springs,
- (4) Estimate flow patterns and zones of mixing,
- (5) Measure potentiometric surface/water table for summer and winter,
- (6) Estimate reservoir geometry, and
- (7) Provide a hydrologic data base for future studies.

Data collected during investigations of hydrogeology and hydrologic conditions in the upper Napa Valley have aided in formulation of a conceptual model of interactions associated with the Calistoga Geothermal field and bordering groundwater. Most data was collected in the 7.9 sq. mi. of the valley floor within the 46 sq.mi. watershed of the upper Napa Valley (Fig. 2).

The Napa Valley watershed is drained by the Napa River and its tributaries. Relief of this watershed within the study area ranges from 255 feet mean sea level (m.s.l.) to over 3,800 feet m.s.l. on the flanks of Mt. St. Helena. Small lateral tributary streams are intermittent under regional climatological and water use conditions. Average slopes within the watershed range from approximately 0.0075 ft./ft. on the valley floor, in the region of Calistoga, to 0.20 ft./ft., from 540 m.s.l. to 3,800 feet m.s.l. As the Napa River descends into the valley floor, it incises older alluvial and fluvial deposits, forming a relief from stream base to surface grade from five to about 25 feet. Annual peak flow in the Napa River in the area of St. Helena, downstream from Calistoga, ranges from 670 cubic feet per second (cfs) to 12,600 cfs for 29 years of record. Flood maps for 100 years indicate that major overflow of the river banks has and would occur in the town of Calistoga. After draining the watershed of the upper Napa Valley, the Napa River flows southeast to San Pablo Bay and eventually the water from the river enters into the Pacific Ocean San Francisco Bay.

The upper Napa Valley is underlain by a thick section of alluvium forming the principal aquifer in the area. Thickness of alluvium in the

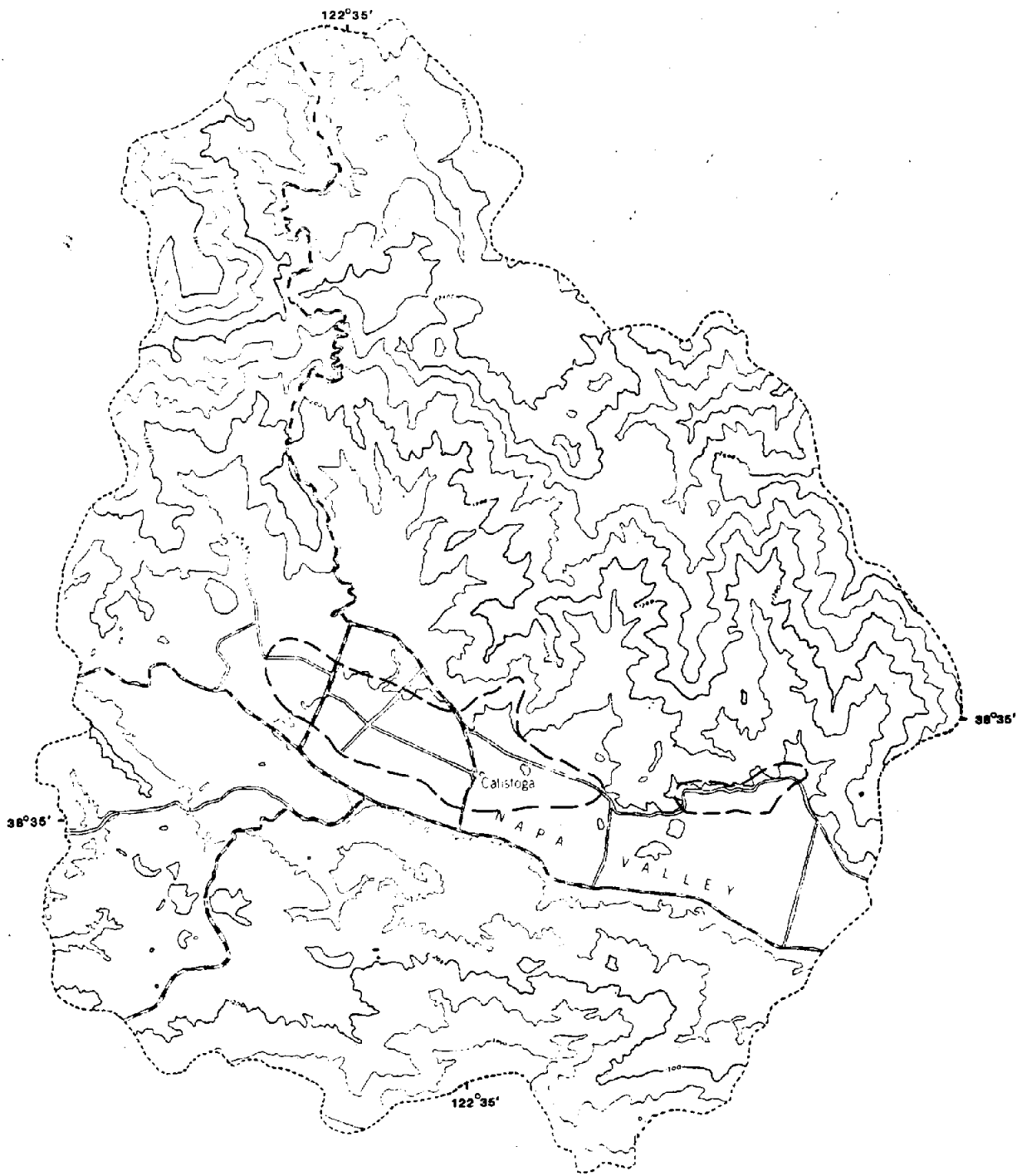


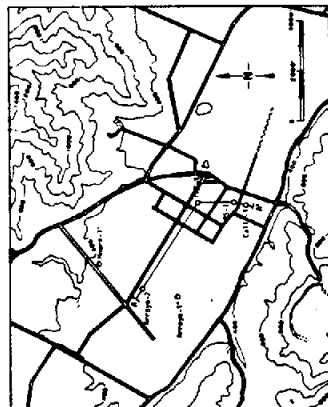
Figure 2. Watershed Area of the Upper Napa Valley.

valley increases progressively from north to south, and from the periphery of the valley toward the Napa River. Within this aquifer, under the town of Calistoga, is a geothermal system defined by elevated concentrations of total dissolved solids (TDS) and elevated temperatures in the local groundwater. The emphasis of this section of the study will be on hydrology of this geothermal system and associative bordering groundwater.

## B. HYDRAULIC CHARACTERISTICS

In his 1973 U.S. Geological Survey Water Resource Investigation publication, Faye presented a comprehensive study of the hydrology of the upper Napa Valley including findings and interpretation of the Calistoga geothermal resource. Faye (1973) considered the Napa River to be an effluent gaining stream which contributes little recharge to the water table. Within the aquifer of the upper Napa Valley Faye (1973) found that "the average hydraulic conductivity of the alluvium, as determined from drillers' logs and from specific capacity data, ranges from 10 to more than 100 feet per day (fpd), depending on the percentage of sand and gravel in the alluvial deposits." His findings further reveal that "the distribution of sand and gravel is irregular and variable but the average values of hydraulic conductivity follow a general pattern: increasing from north and south, and from the peripheries of the valley toward the Napa River." Thus along any section that crosses the valley, the average hydraulic conductivity near the Napa River ranges from approximately 40 fpd near Calistoga to more than 110 fpd near St. Helena. Faye (1973) calculated the hydraulic conductivity (k) in the center of the valley to range from 30 to 50 fpd, with bordering "k's" of the aquifer, toward the hills, to be in the range of 0.5 to 30 fpd. Faye (1973) states that the yield from wells in the alluvium range from approximately 50 gallons per minute (gpm) to over 3,000 gpm from Napa Valley wells, depending on the number, thickness, and interconnection of gravel and sand lenses, and screening in a particular well. Faye (1973) indicated that the hydraulic conductivity for the underlying Franciscan deposit to be in the range of  $10^{-4}$  fpd or less. Younger Sonoma Volcanic deposits tend to have k's in the range of  $10^{-2}$  to  $10^{-3}$  fpd. Faye also stated that the shallow water aquifer in the alluvium is unconfined. He also found that at depths ranging from 50 to 100 feet below land surface, drillers generally encountered confined, hydrothermal water ranging from 29.5°C (85°F) to 120°C (248°F) in the region of Calistoga.

Hydrologic and geologic data collected by the staff of the California Division of Mines and Geology (CDMG) during their 1979-80 field investigation yielded new information about the character of the primary aquifer of the upper Napa Valley with specific emphasis on the Calistoga geothermal system. By drilling into the aquifer/aquitard system, Taylor and others (1981) defined the stratigraphy of the upper Napa Valley basin to be composed of alternating deposits of highly permeable alluvial flood plain and channel deposits consisting of sands and gravels with interbeds of less permeable to impervious volcanic ash deposits. All units appear to dip approximately 9° toward the southwest (Plate 1). Taylor and others (1981) further states that "the alluvial units of gravels and sands are probably not continuous for any great



lateral extent, for these lenticular and cutoff beds formed in a fluvial environment and were dissected and then inundated by subsequent flood plain and channel deposits."

Field investigations by CDMG found that, "wells located in close proximity to one another and drilled to the same depth could produce highly variable rates of water discharge." (Taylor and others, 1981). In addition, it was found that the effectiveness of volcanoclastic deposits to act as a vertical barrier to groundwater flow was dependent upon "(1) clay mineralogy, (2) thickness of the ash fall or ash-flow tuff units, and (3) lateral continuity of these units." The CDMG believes that weathered pyroclastic material, originally composed of aerially deposited, quartzofeldspathic glass shards, had undergone almost complete alteration to expansive smectite clay minerals. Relatively thick sequences of these deposits could therefore represent a significant vertical barrier to groundwater flow.

Early studies by Young and others (1980) concluded from well data and geophysical studies that the average depth of valley alluvium and alternating volcanoclastics was on the order of 400 feet. Later analysis by Taylor and others (1981), however, revealed that a 2,000 plus foot geothermal exploration hole in Calistoga failed to hit the pre-Sonoma Volcanic basement surface. Taylor and others (1981) concluded that the basement of the aquifer must be of "highly variable relief," and stated that this relief indicates a "deepening structural basin plunging to the southwest." Like Waring (1915), Taylor and others (1981) concluded that the existence of a fault aligned with the topographic axis of the valley provides a conduit for ascending hydrothermal water. The water is apparently driven by recharge at higher elevations with the subsequent rise due to buoyancy of the heated fluids following a period of deep circulation. From this hydrothermal convection model, Taylor and others (1981) suggest that the potentiometric surface is dependent on the recharge area being at high elevation, the existence of confining beds in the aquifer/aquitard system, and geothermally-induced density differences of the groundwater. From calculations using approximate volume of sediments to be 640 feet deep by 5.8 square miles of geothermal extent, Taylor and others (1981) determined a tentative mean reservoir thermal energy of  $0.52 \times 10^{18}$  Joules. Using a specific yield factor of 6.95 percent and assuming that only 10 to 15 percent of the geothermal water can realistically be withdrawn, the geothermal aquifer yield was calculated to be on the order of 13,500 to 20,250 acre-feet ( $4.4(10)^9$  gallons). The assumption made by the staff of CDMG of realistic withdrawal of 10 to 15 percent assumes that inflow plus the effective capture of natural discharge, minus an acceptable change in storage in the aquifer, results in a safe yield of the aquifer. Concerning these assumptions it should be stated that no documentation is provided by CDMG of potential recharge, groundwater depletion, or effectiveness of capture of natural discharge to determine the safe yield of the Calistoga geothermal system.

#### C. METHODS AND ANALYTICAL TECHNIQUES

During initial surveys of the Calistoga Geothermal Field, a boundary was defined on the basis of previous investigations and includes 46 square

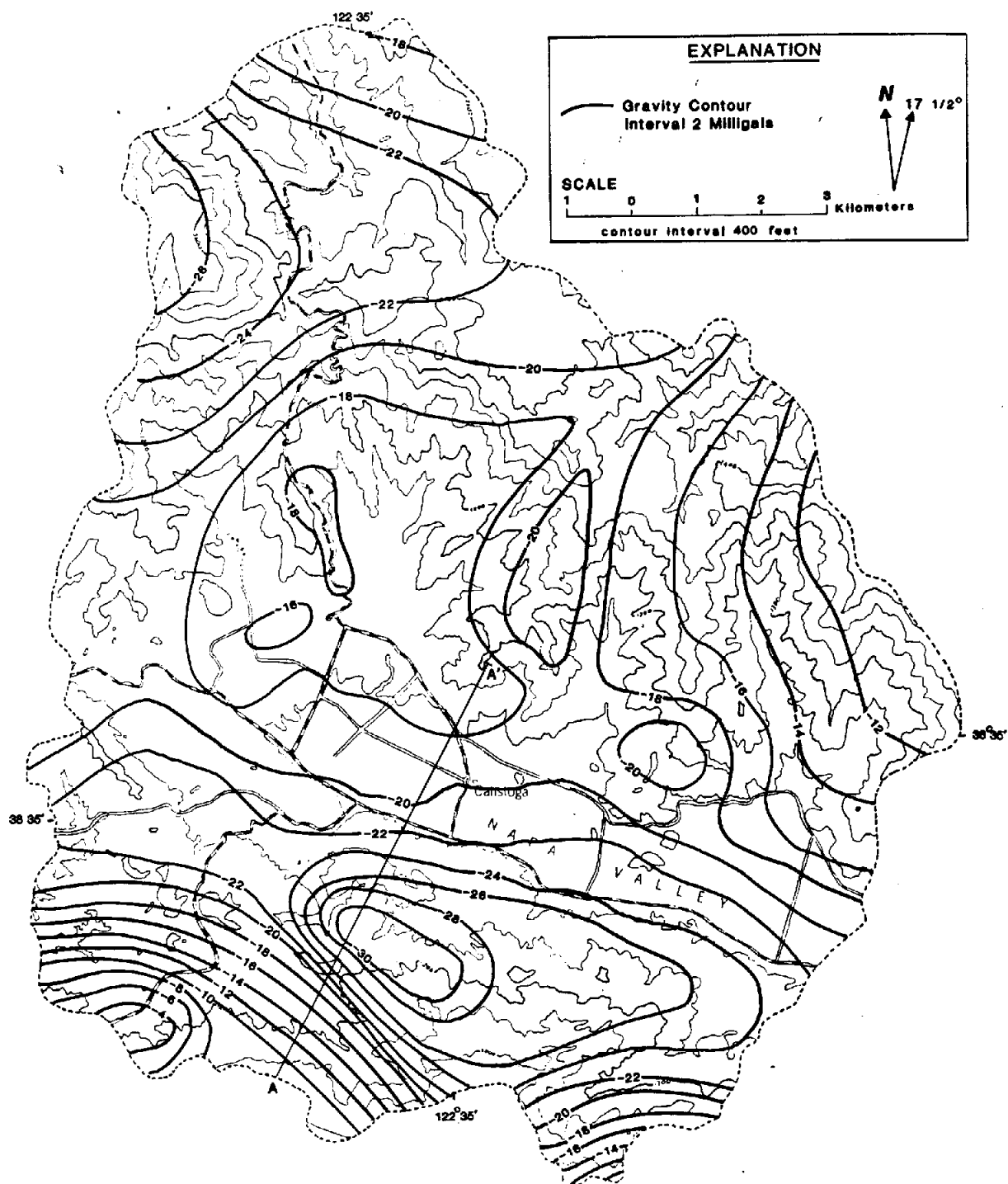
miles of valley floor and surrounding watershed as shown in Figure 2. Within this watershed is one large and possibly a second smaller geothermal system and a potential recharge area.

An important task of this hydrologic investigation is to establish a data base for the comprehensive review of existing hydrological data. Particular emphasis is placed on the review and analysis of local and regional hydrogeologic, hydrogeochemical, and hydrothermal conditions, along with aquifer/aquitard stratigraphy. The characterization of groundwater flow-patterns associated with Calistoga's geothermal system requires an integration and interpretation of data associated with the disciplines of geophysics, soil chemistry, hydrochemistry, hydrogeology, and classic hydrology. The use of gravimetric geophysics, soil mercury and certain hydrochemical indicators allows for quantitative speculation on possible patterns associated with fracture flow direction, potential sources of recharge into the alluvial system, possible source(s) of heat for thermal buoyancy, and indication of upwelling zones from fractured bedrock into the alluvial system. Once the thermally-charged groundwater enters into the upper Napa Valley alluvial aquifer/aquitard system, hydrochemistry and classic hydrologic analysis is used to determine the velocity of flow and to locate zones of mixing. In addition, hydrochemical analysis provides indicators for tracing groundwater bodies associated with the geothermal system.

#### Gravimetric Analysis

Both detailed and reconnaissance-level gravity surveys were conducted within the area of study by CIMG in the early 1970s and in 1980. Regionally, gravity values in the California Coast Ranges decrease toward the northeast. Chapman and Bishop (1974) identified this trend in the upper Napa Valley to be on the order of one-half milligal per mile. This regional trend is a result of increased thickening of the earth's crust toward the east from the coastline of California. Anomalous features identified by Chapman and others (1982) include two prominent northwest-trending negative gravity anomalies. The larger of the two anomalies is a 30 milligal gravity low, approximately one to 1 1/2 miles southwest of Calistoga and slightly elongated parallel to the valley floor (Fig. 3). This anomaly has a maximum amplitude of about 15 milligals from the regional gravity, and continues to the southeast gradually decreasing in amplitude. A second gravitational anomaly with a smaller amplitude is located northeast of Calistoga. This anomaly's lowest point is a set of 14 milligal lows trending northwest. Figure 4 (after Chapman and others, 1982) is a cross section showing topography and gravity drawn across the southernmost gravitational low and the town of Calistoga. The two-dimensional anomaly superimposed on regional trends shows a good correlation with lithologies characteristic of the upper Napa Valley. Relatively high gravitational attraction is believed to be related to the dense rock of the Franciscan assemblage, southwest of Calistoga. Accordingly, the two gravitational lows bounding Calistoga can possibly be correlated with the tuffaceous units of the Sonoma Volcanics. Chapman and others (1982) proposed that the principal reservoir southwest of Calistoga is a large syncline and/or graben-like depression filled with Sonoma Volcanics to a depth greater than 2,000 feet below sea level. No gravimetric interpretation is presented in this model of the effect of a magmatic body onto gravity profiles, or the effect of alluvium and other unconsolidated sediments.

Figure 3. Complete Bouguer Gravity Map of Upper Napa Valley Region.



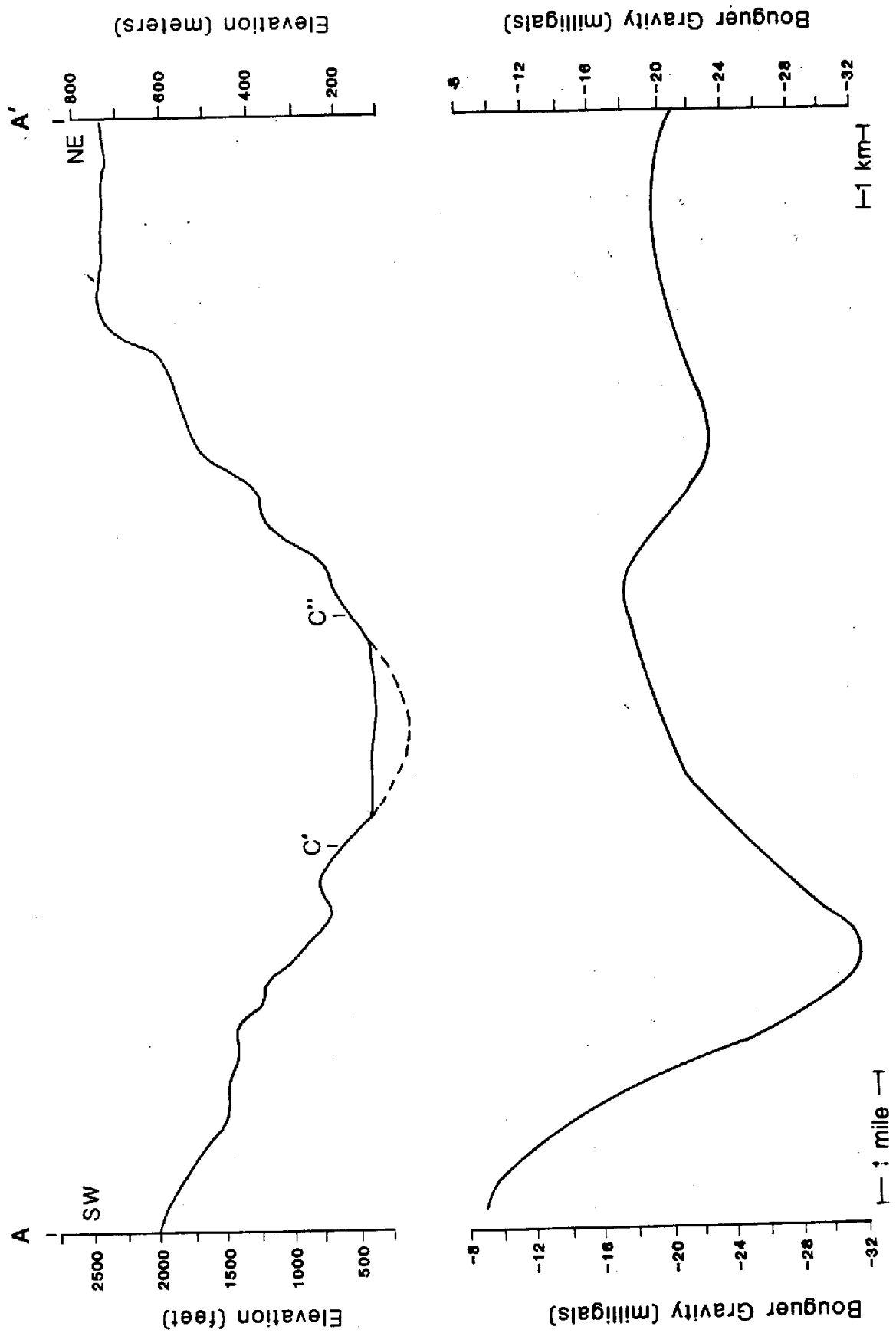


Figure 4. Gravity and Topographic Profiles of Line A-A' of the Upper Napa Valley.

Magmatic bodies could range from a density of  $2.2 \text{ g/cm}^3$  for molten silic rock to about  $2.8 \text{ g/cm}^3$  which represents a solidified andesite-basalt magma chamber. If a molten magmatic body exists, the prevalent lows in the region of the upper Napa Valley could be from a combination of a thickness of tuffaceous Sonoma Volcanics and the magmatic body. This would provide two essential elements of a geothermal system: (1) a porous reservoir, and (2) a heat source. In contrast, a solidified andesite-basalt magmatic body with a density of approximately  $2.8 \text{ g/cm}^3$  could be masked by a combination of average Franciscan complex (density =  $2.65 \text{ g/cm}^3$ ) and Franciscan greenstone (density =  $2.65 \text{ g/cm}^3$ ). Fracturing and/or hydrothermal alteration will lower the overall density and may also effect identified gravitational lows. The effect of magmatic bodies on local gravitational anomalies cannot be confirmed with gravitational data alone, and will need to be interpreted by other geophysical or chemical indicators.

Alluvium, ranging from  $1.5$  to  $2.4 \text{ g/cm}^3$  could appreciably effect the localized gravitational trend. However, because of its possible thickness relative to the potential depth of Sonoma Volcanics, its effect could be minor. No strong indication can be seen on the isogal map over the area of the basinal alluvium.

In conclusion, gravitational data identifies a thick unit of tuffaceous Sonoma Volcanics which could represent the main reservoir of the Calistoga Geothermal Field, southwest of the town under Diamond Mountain. Possible correlation of local magmatic bodies with local gravitational lows are inconclusive at this time and will need additional investigation to define a definitive relationship.

#### Seasonal Measurements of Groundwater Levels and Chemistry

Measurements of water levels from approximately 140 wells were collected in the summer of 1984. The method of collection was lowering a calibrated set of covered wires into the well bore and recording the length when contact was made with the standing water. Water levels in the wells represent static conditions. Measurements were correlated to ground level and then interpolated, using shallow topographic profiles, to elevation relative to mean sea level. The mapping of the distribution of standing water levels in the upper Napa Valley defines the potentiometric surface.

Seasonal variation of hydraulic head, in and bordering the geothermal system, was determined by remeasuring water levels in 25 wells during the winter of 1985. The collection of winter water levels used the same methodology as during the summer measurements. Major ion chemistry was collected from these wells to determine seasonal changes in chemical character. Chemical indicators tested for include: chloride, boron, iron, and sulfate. Collection methodology included pumping for approximately 15 minutes, or at a minimum, three casing volumes and storage in plastic laboratory bottles. The Desert Research Institute Laboratory of Reno, Nevada performed the analysis.

Results of summer head measurements are plotted with interpolated equipotential lines on Figure 5. Contours are at 10 foot intervals. In the upper Napa Valley groundwater levels range from above 410 feet m.s.l., at the head of the valley, to below 280 feet m.s.l. down valley, toward the limit of the defined study area. Along the axis of the valley, from the Geysers to Pachetau's, the grade of the potentiometric surface ranges from .005 ft./ft. to .04 ft./ft., with an average of .01 ft./ft. Southwest of this axis, the potentiometric surface falls approximately .008 ft./ft. Equipotential lines in the northeast border of the valley principally follow a down valley component. Potentiometric domes occur in the alluvial groundwater associated with the Geysers and Pachetau's. Potentiometric lows are associated with Crystal Geyser and Sterling wells. From Pachetau's potentiometric high toward the Crystal Geyser low, the potentiometric surface decreases at a rate of .02 ft./ft.

Seasonal variation of water levels from the summer of 1984 to the winter of 1985 in the upper Napa Valley is presented in Figure 6. Summer to winter water level changes ranged from 59 feet in bordering wells of the upper valley to no change in selected geothermal wells. Generally wells bordering the geothermal system rose in water level in the winter and fell in the summer, with an associative decrease of temperature in the winter and a rise in the summer. Water in these wells also showed a general seasonal decrease in chloride and boron, and an increase in iron and sulfate (Fig. 7). Well water inside the zone of dominant geothermal activity showed only slight variation in chemistry associated with changing seasonal conditions.

Water level measurements indicate that the groundwater is moving dominantly down valley in alluvial aquifers. Using Faye's 40 fpd as a local hydraulic conductivity, the resultant downvalley groundwater flux is approximately 1.3 feet per day, using an average 30 percent aquifer porosity. The potentiometric domes, probably represent zones of concentrated geothermal upwelling. Local potentiometric lows are most likely associated with areas of pumpage with inadequate groundwater influx.

It is suggested that in the upper Napa Valley the groundwater potentiometric surface is composed of upwelling thermal waters associated with a mid-valley bedrock fissure and influxing nonthermal water recharged from surrounding uplands. Mixing zones of geothermal and nonthermal waters result in a decrease in both temperature and chemical character during periods of winter borderland recharge in the alluvial aquifer. The mid-axis geothermal system expresses little effect from seasonal rainfall variation and maintains relatively consistent temperatures, chemistry, and water levels.

#### Soil Mercury

To assess the potential of a soil mercury geochemical survey that would define possible geothermal flow patterns in the region of Calistoga, 53 soil samples were collected along lines both perpendicular and parallel to the topographic axis of the valley. The soil samples were collected during the summer and fall of 1984-85 and were extended beyond the area

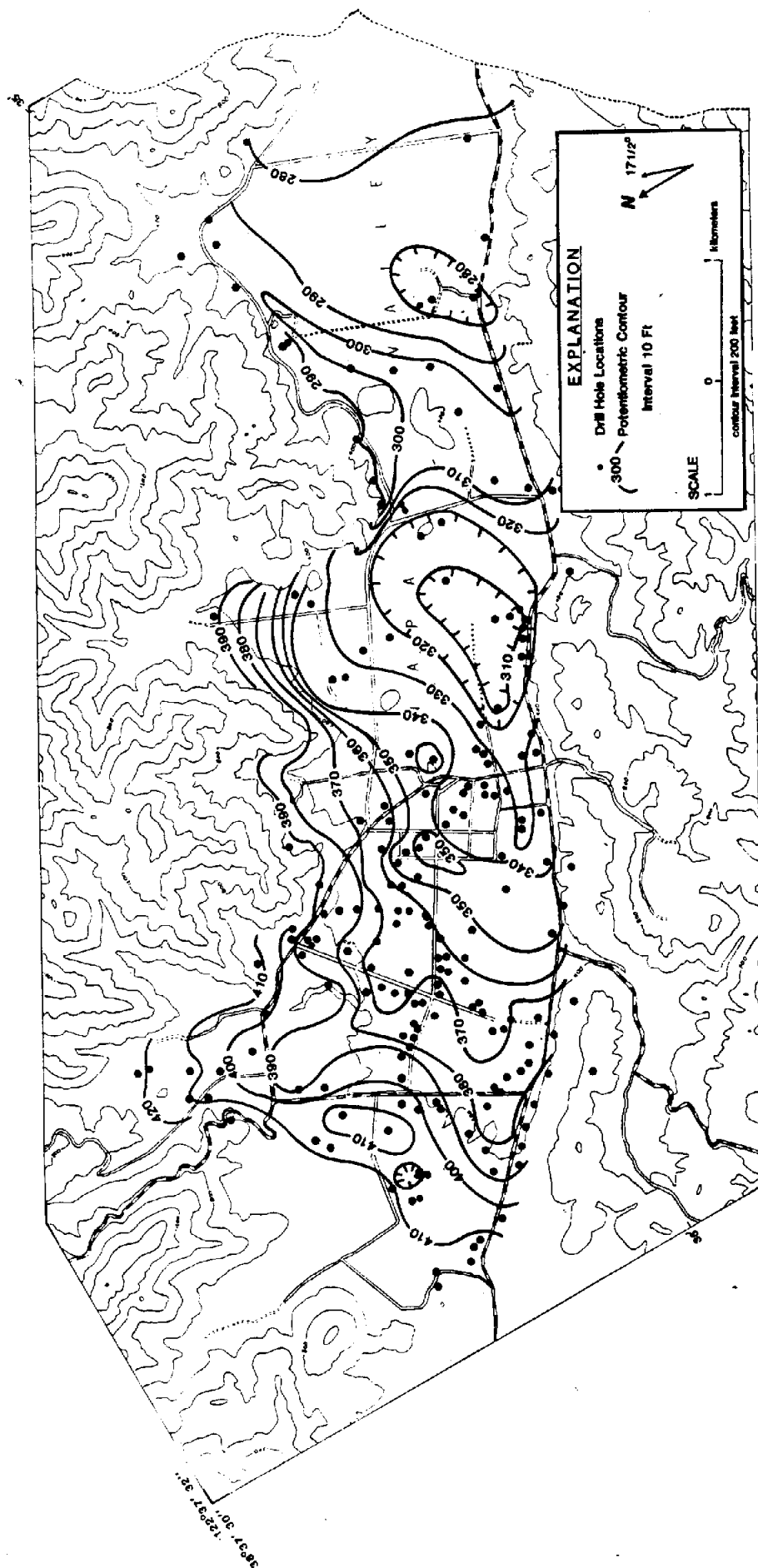


Figure 5. Map of the "summertime" potentiometric surface within the Upper Napa Valley. Data points based on water-level measurements from 140 water wells.

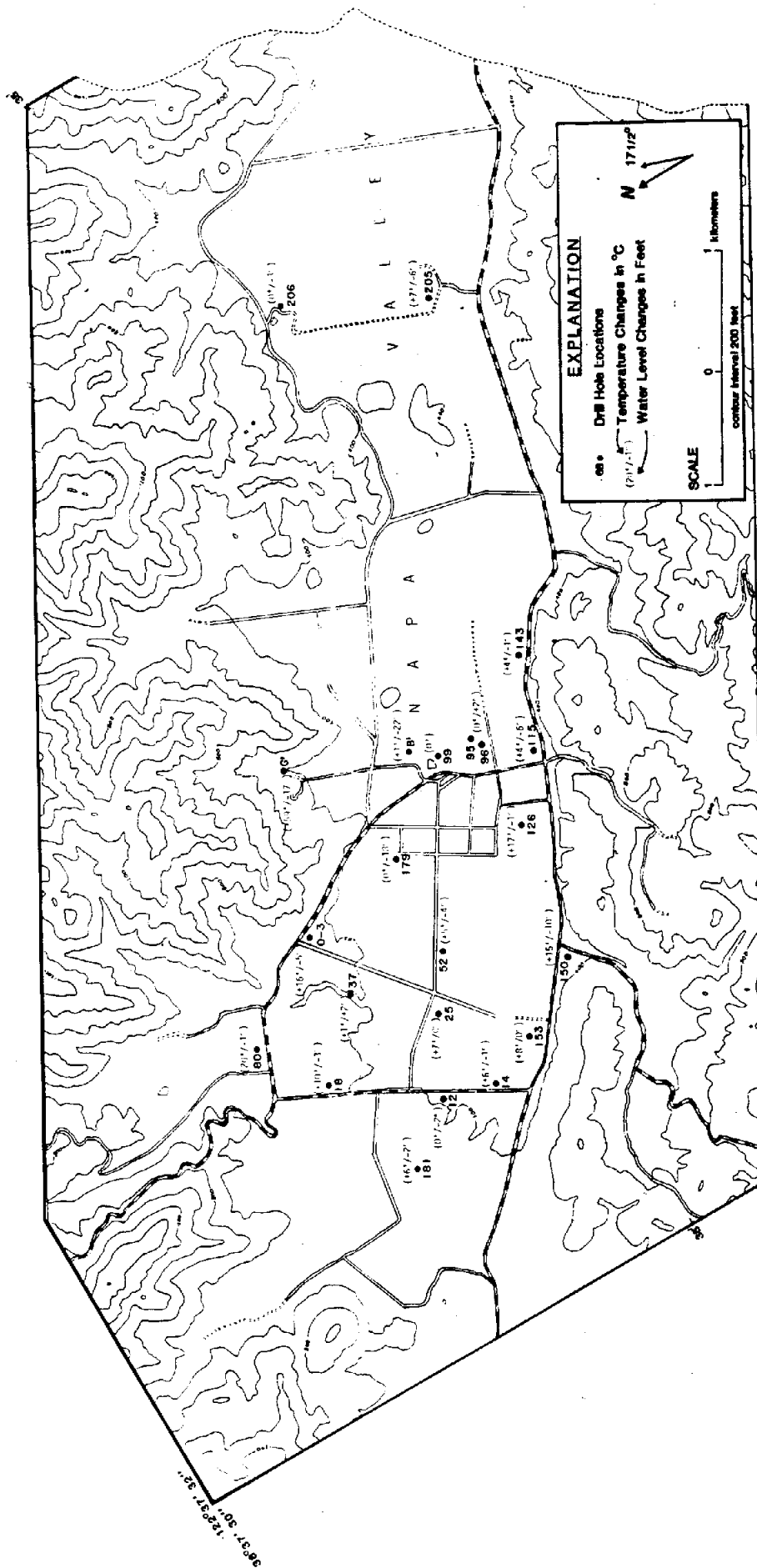


Figure 6. Changes in Water Levels and Temperature from Summer 1984 to Winter 1985 in the Upper Napa Valley.

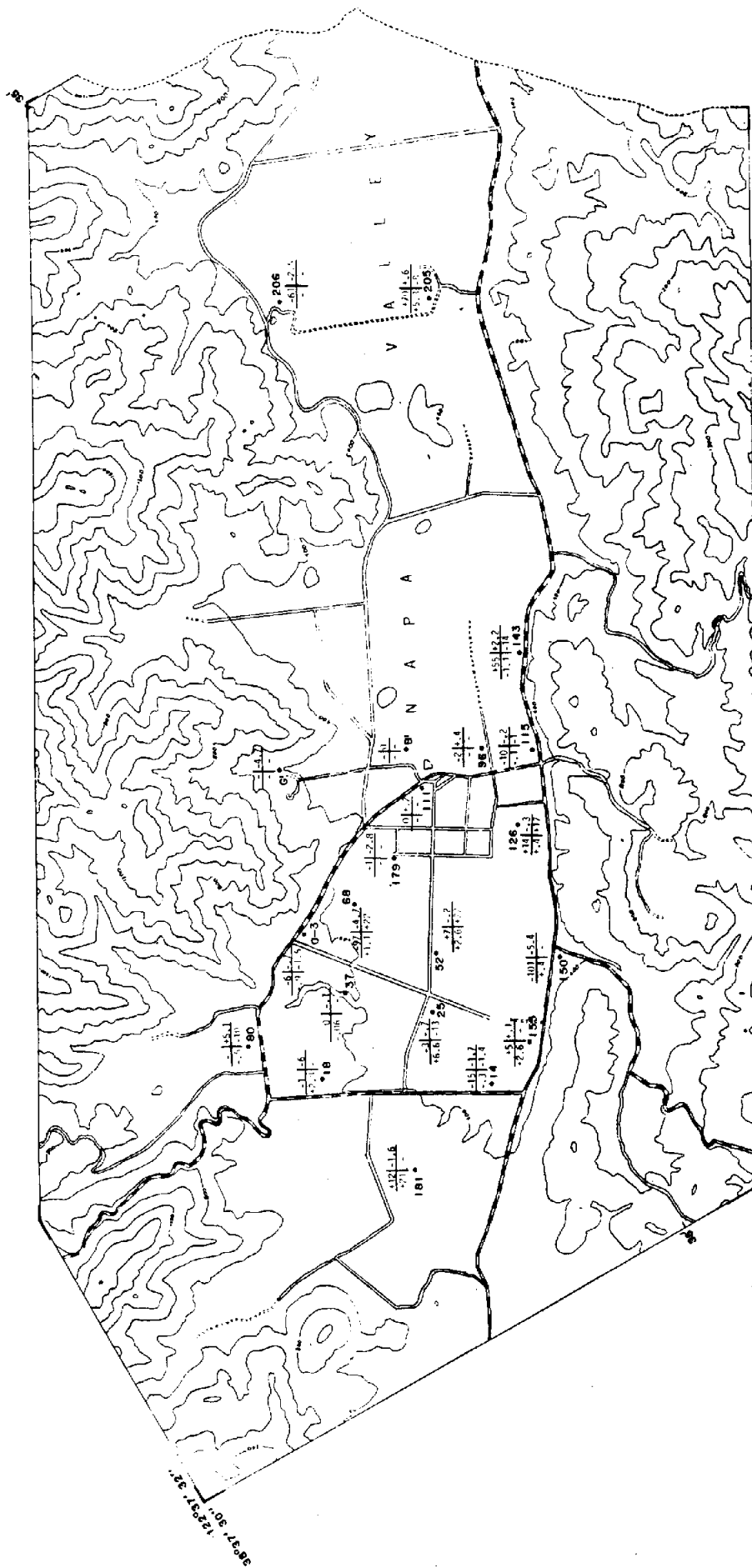


Figure 7. Changes in well water chemistry from summertime to wintertime conditions. Number in upper lefthand corner is the change in chloride concentration; upper right boron; lower left, sulfate; lower right, iron.

of known geothermal concentration, both up and down valley. Soil for the mercury survey was collected from the upper foot of the soil profile and placed in a plastic bag for transportation to the laboratory. In the lab the samples were wet sieved, filtered, air dried, and pulverized. The pulverized soil samples were then acidified with nitric acid and allowed to sit for four days. The samples were then diluted with water and analyzed with an Atomic Absorption Spectrophotometer using the Cold Vapor Technique.

Within the area of study soil mercury ranged from 14 parts per billion (ppb) downvalley from Calistoga to above 3.2 parts per million (ppm) in the town of Calistoga. Figures 8 and 9, respectively, show the concentrations at each sampling point and an interpolated isocontour map of mercury contour lines. Two locations were studied in detail using soil mercury surveying techniques in the upper Napa Valley: (1) the main Calistoga aquifer, and (2) a small anomaly located downvalley from Calistoga. In transects perpendicular to the axis of the valley a definite skew of increasing mercury values is apparent toward the southwest. Toward the northwest, soil mercury concentrations tend to decrease except along the transect through Calistoga where it first decreases, then rises to over 1.4 ppm.

The apparent southwestward increase in soil mercury is toward Diamond Mountain, a region of potential recharge for the alluvial geothermal aquifer. High soil mercury values suggest a possible degassing of the geothermal waters through fissures in the bedrock in this area. A conceptual model of thermal water flux and mercury degassing is presented in a series of cross-valley profiles (Figs. 10 through 15). This model indicates that mercury-charged water, influxing from the southwest, degases along multiple fissures parallel to the axis of the valley, and then enters through the main fissure along a line trending parallel to the valley axis (from Pacheteau's spa to the Geyser). Thermal water influx is indicated by elevated groundwater-chloride values. This is in agreement with interpreted gravity data of a thick reservoir of principally Sonoma Volcanics under Diamond Mountain, southwest of Calistoga. The mercury data further indicates that either a magmatic body degassing mercury vapors is located southwest of Calistoga and/or that the thermal water is mobilizing mercury already present in the Sonoma Volcanics.

Two additional elevated mercury anomalies occur at the northeast border of the upper Napa Valley, as seen on Figure 8. Just northeast of Calistoga an elevated level of soil mercury above 1.4 ppm is also correlated with slightly elevated, although generally decreasing, groundwater chloride levels, as seen on line C-C' in Figure 13. In the location of the Old Tamani Ranch downvalley from Calistoga, elevated levels of soil mercury, as high as 2.8 ppm, show a strong correlation with an elevated groundwater chloride value of about 200 ppm (Fig. 9). These elevated levels of mercury probably represent a fissure system of undefined length along part of the northeast boundary of the upper Napa Valley. Identified soil mercury anomalies are skewed toward localized geothermal anomalies bordering the valley. This combination of skewed mercury anomalies and gravitational lows probably indicate separate Sonoma Volcanic reservoirs in the uplands bordering the valley and/or

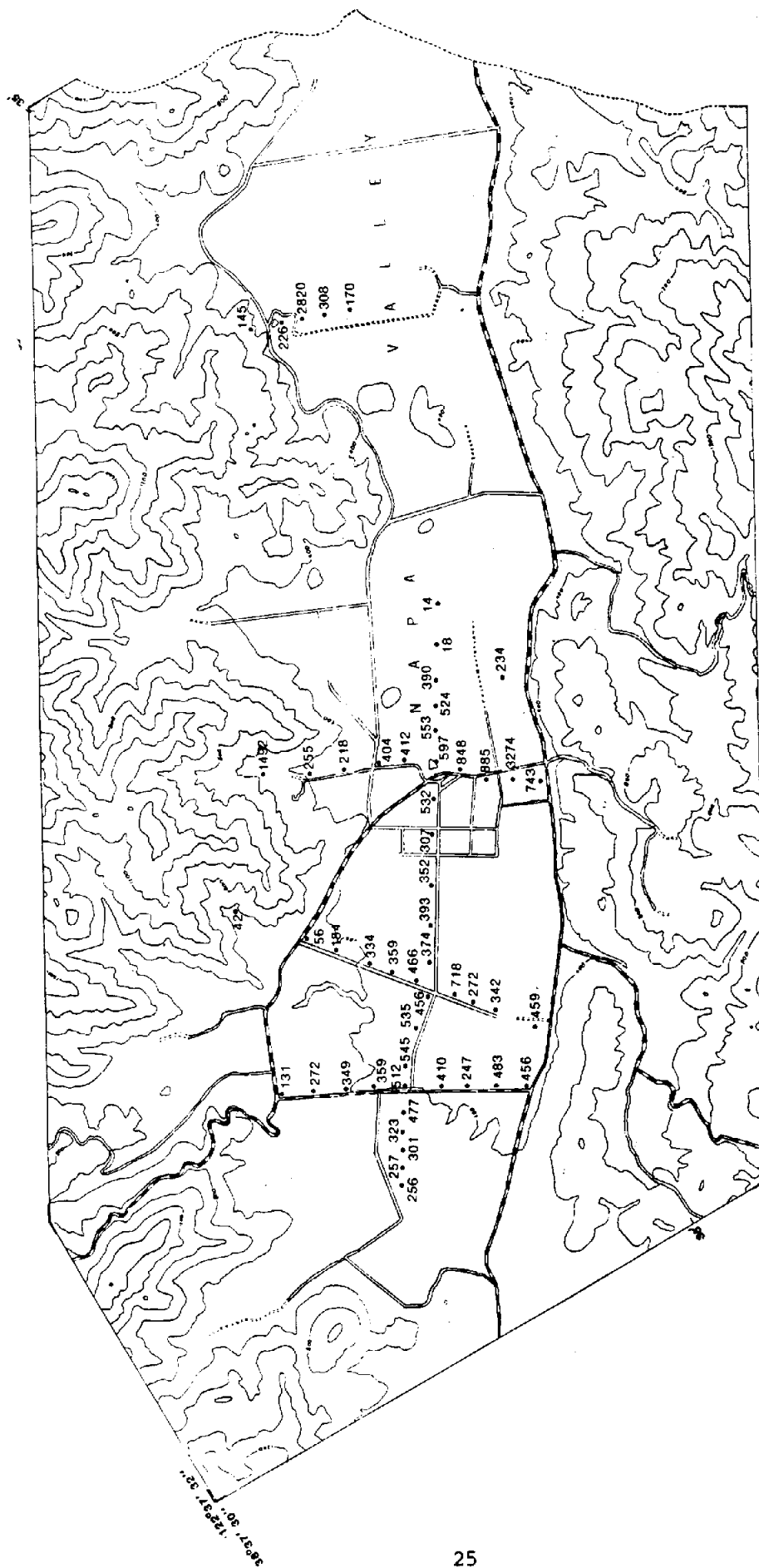


Figure 8. Map of sample locations and concentrations of soil mercury.

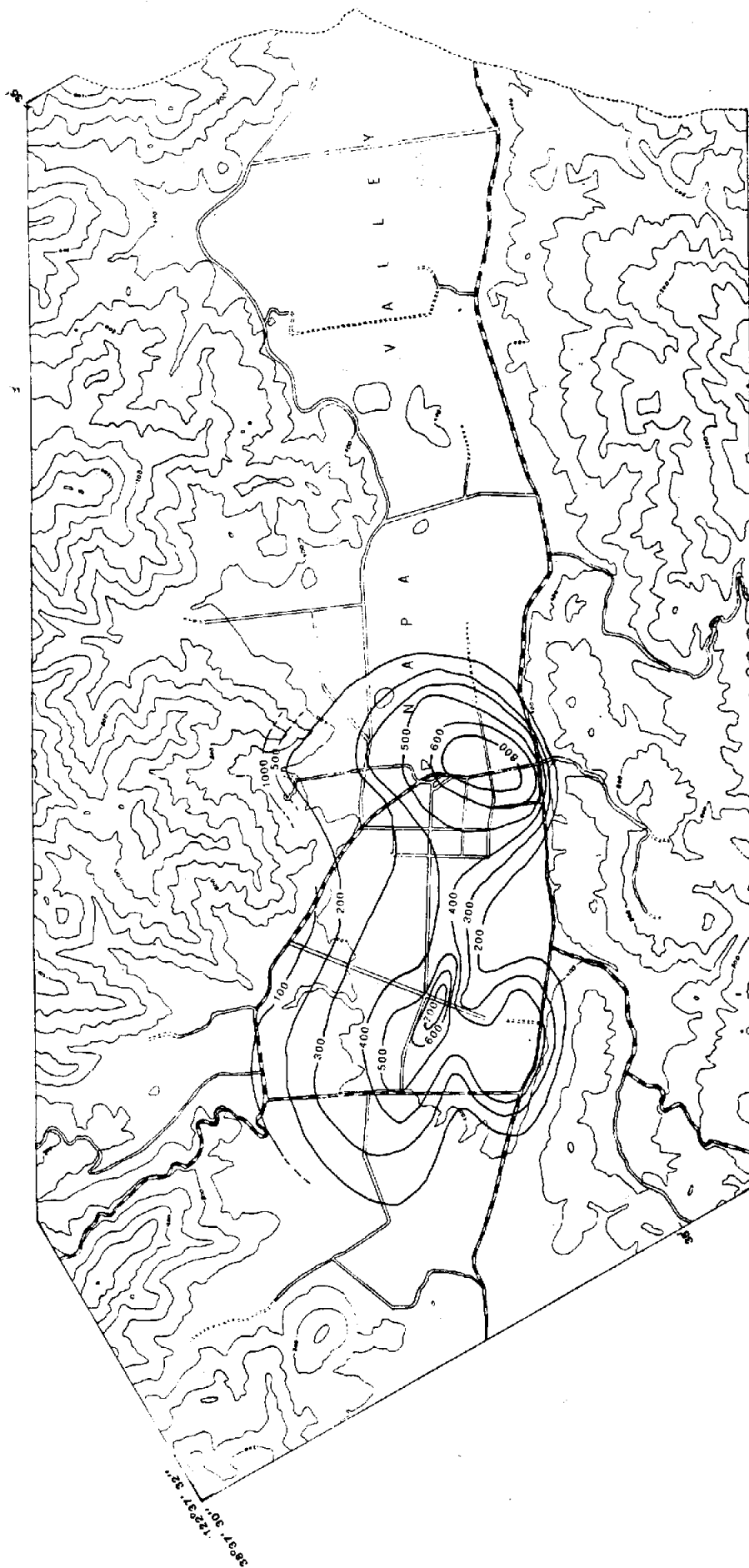


Figure 9. Contour map of soil mercury concentrations.

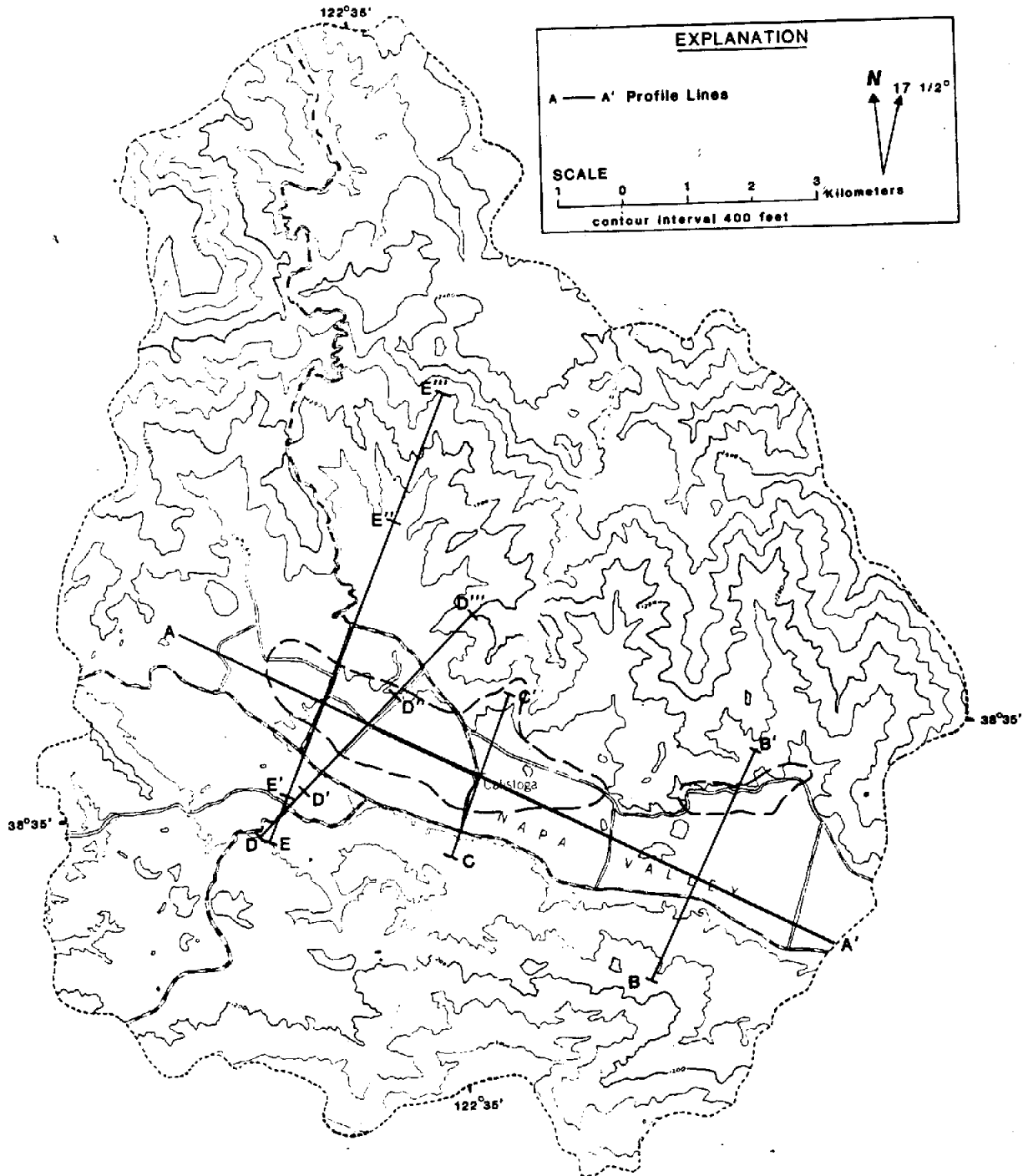


Figure 10. Index map for mercury, chloride or gravity topographic profiles for Figures 11 through 15.

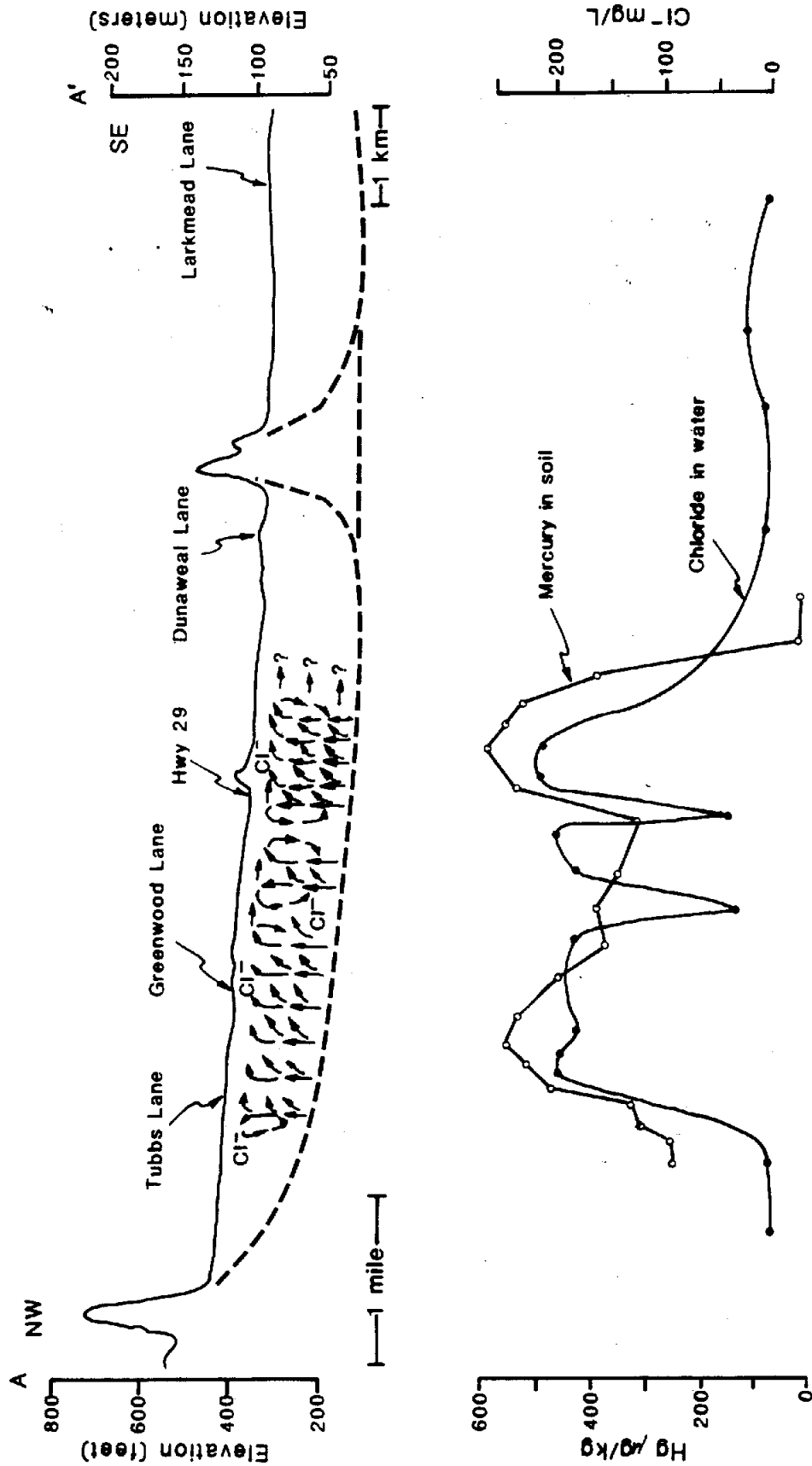


Figure 11. Mercury, chloride and topographic profiles of line A-A'.

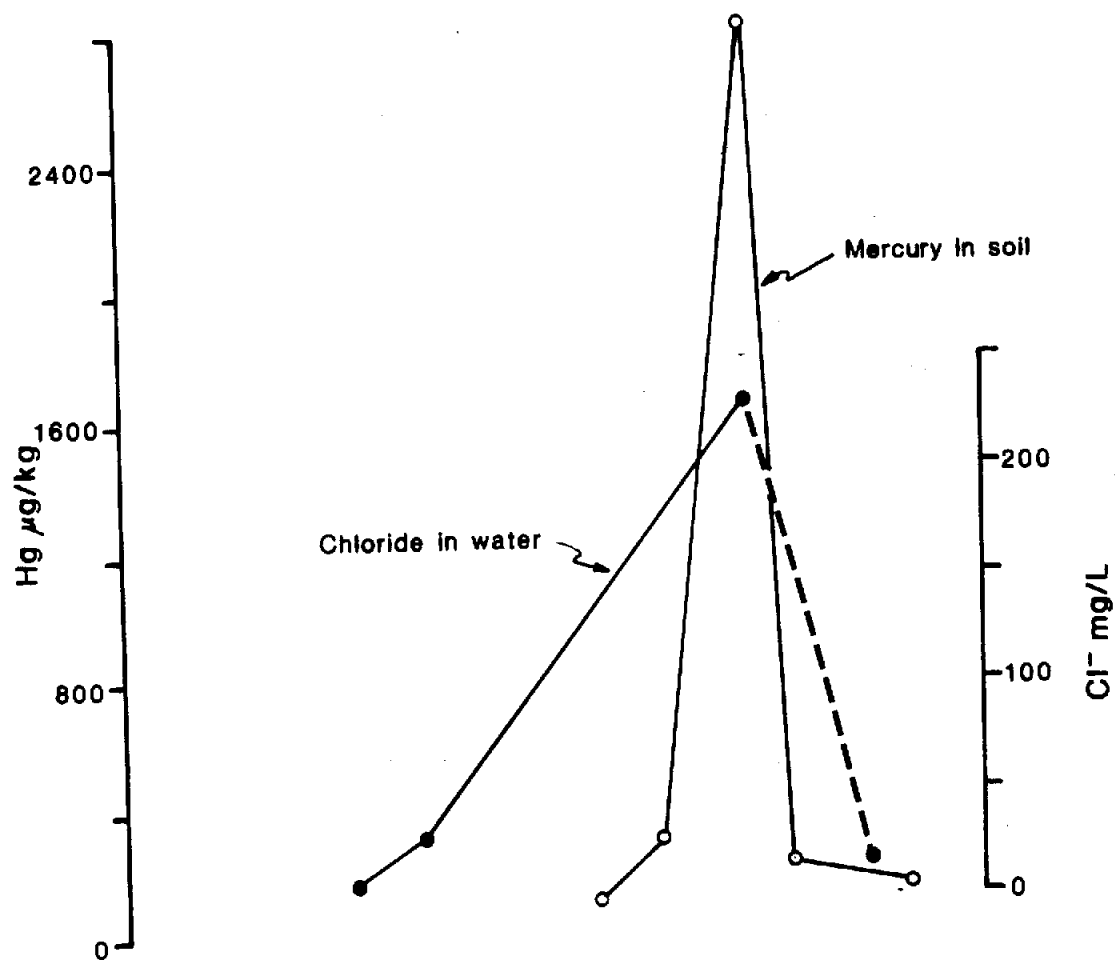
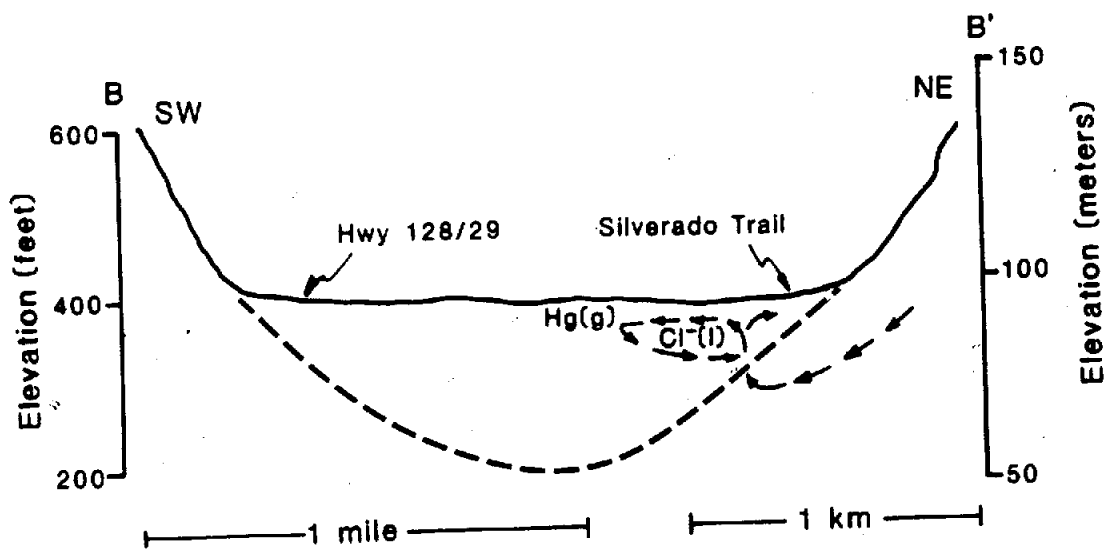


Figure 12. Mercury, chloride and topographic profiles of line B-B'.

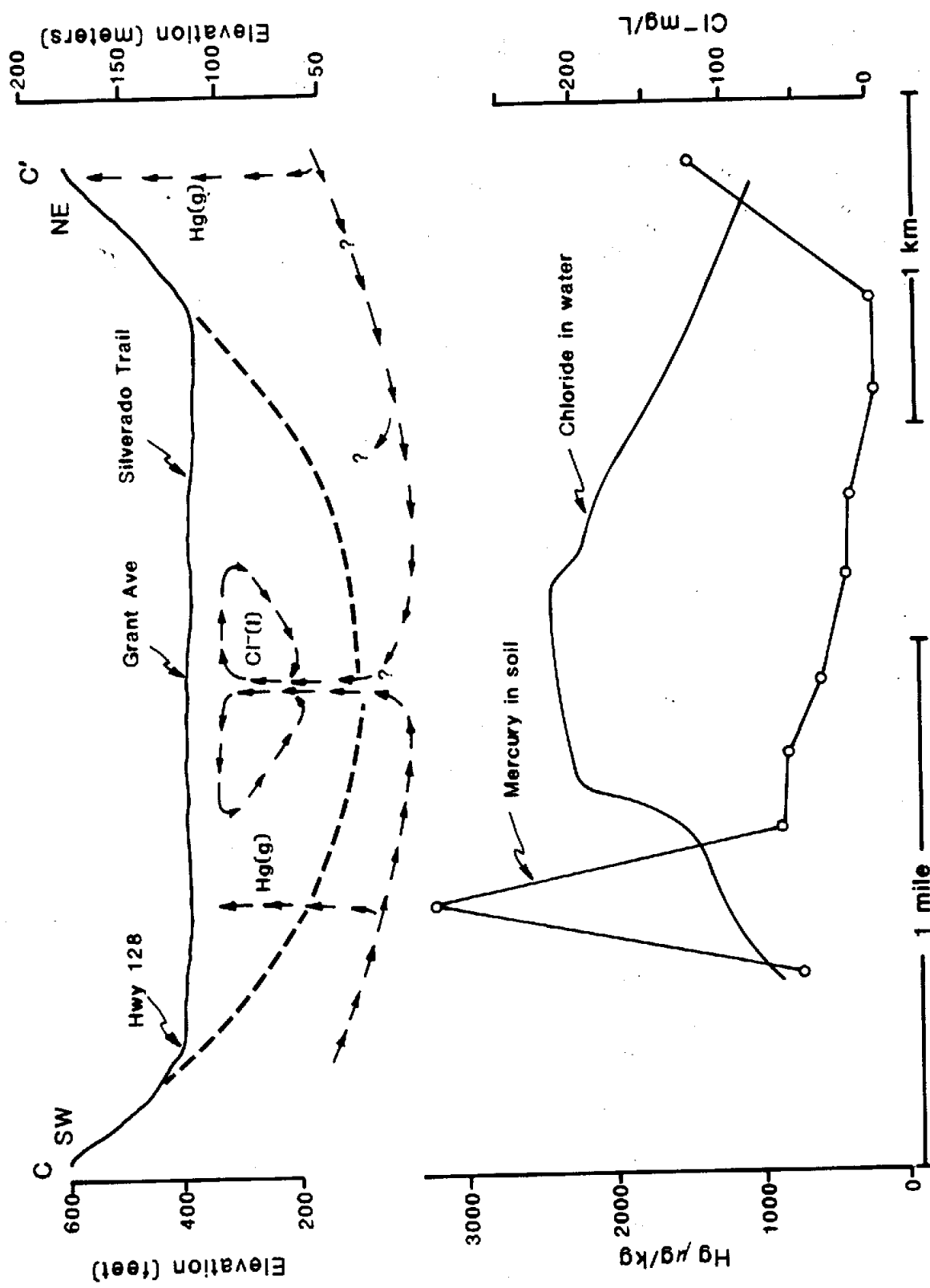


Figure 13. Mercury, chloride and topographic profiles of line C -C'

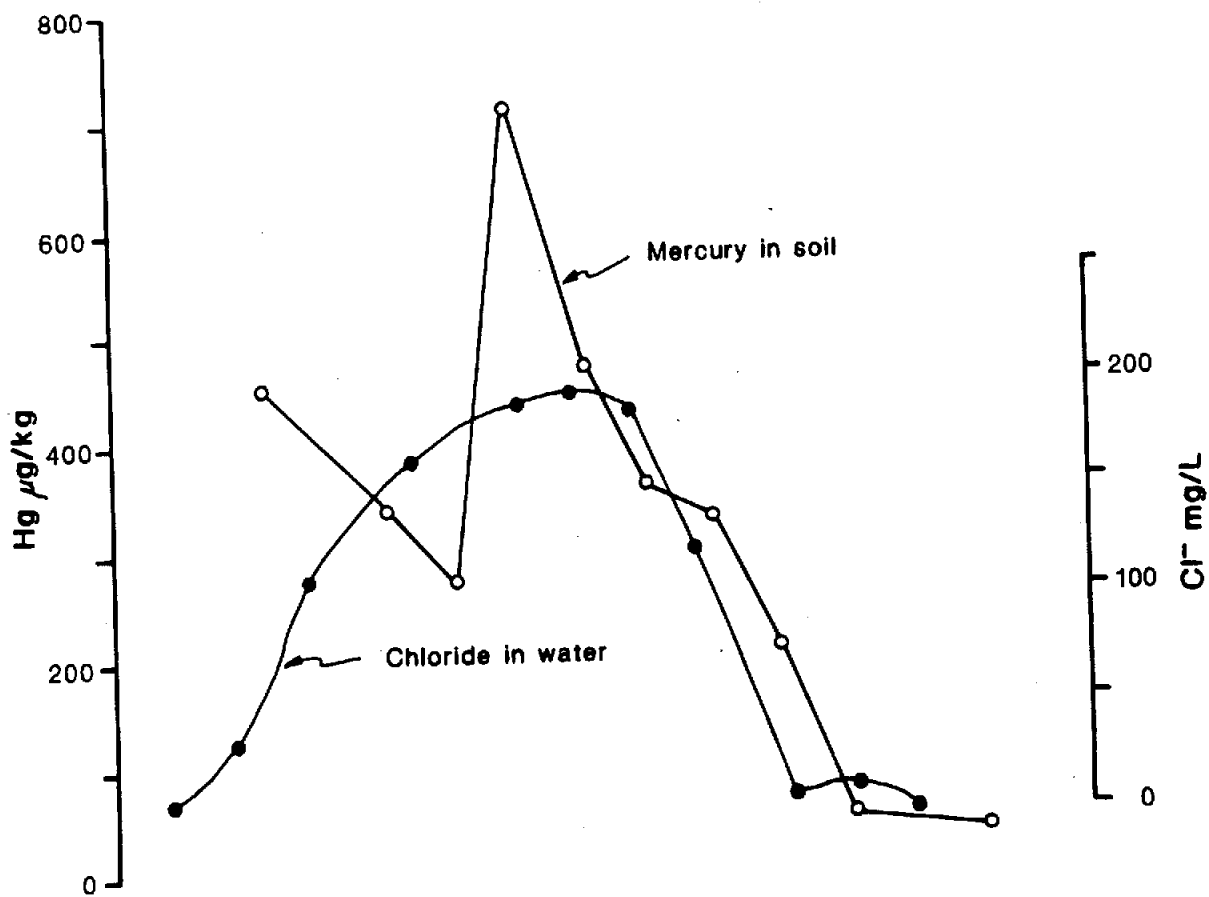
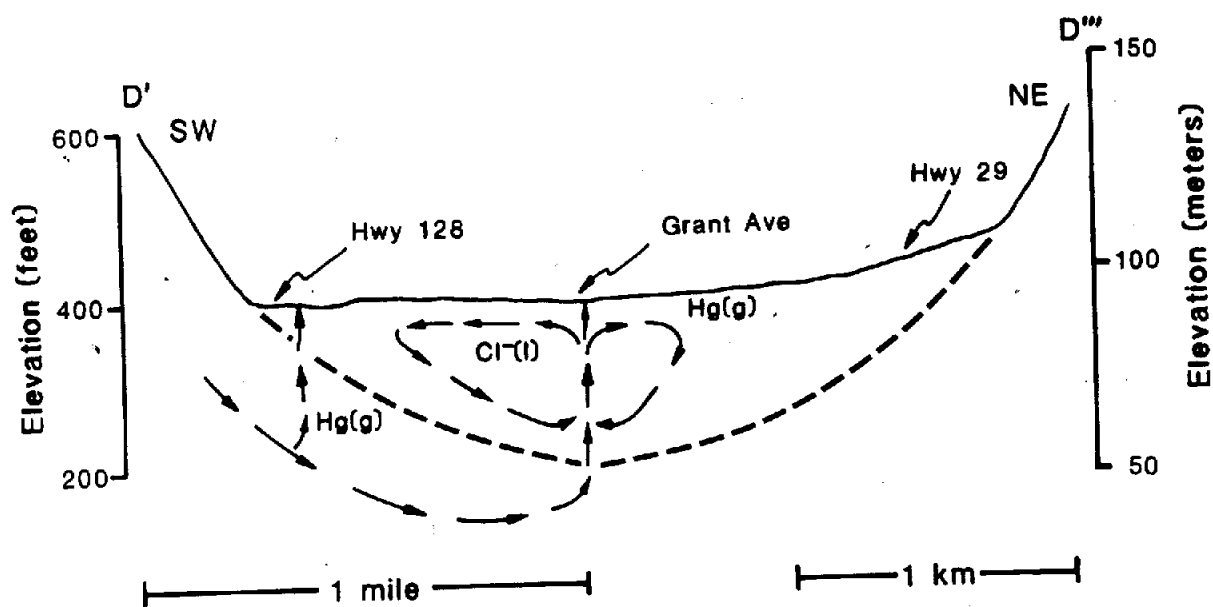
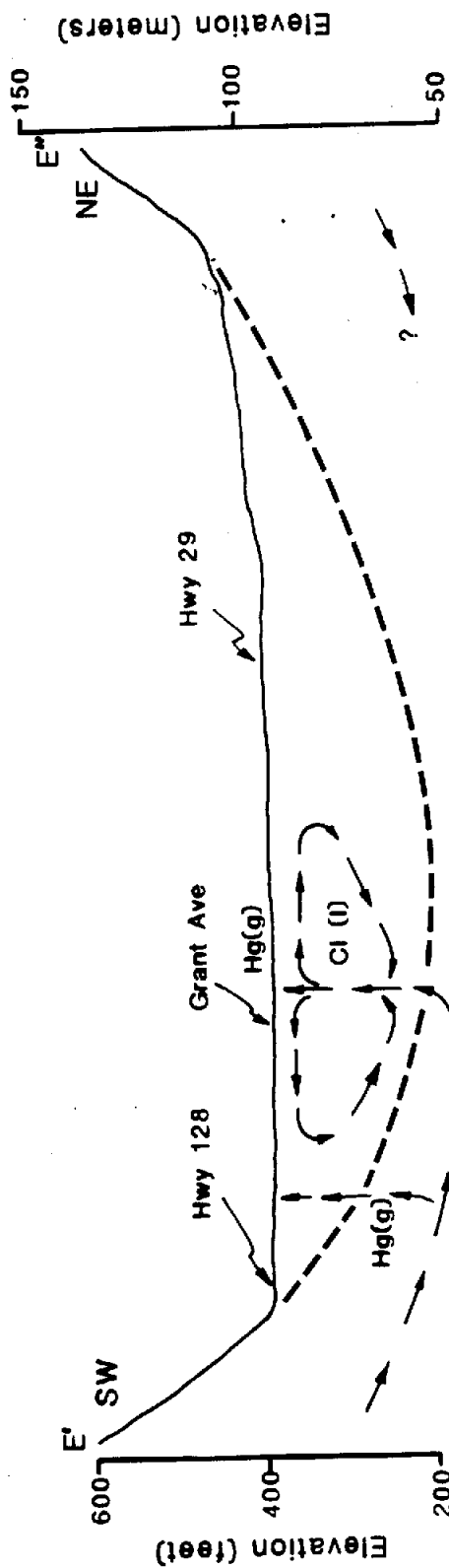


Figure 14. Mercury, chloride and topographic profiles of line D'-D'''.



1 km

1 mile

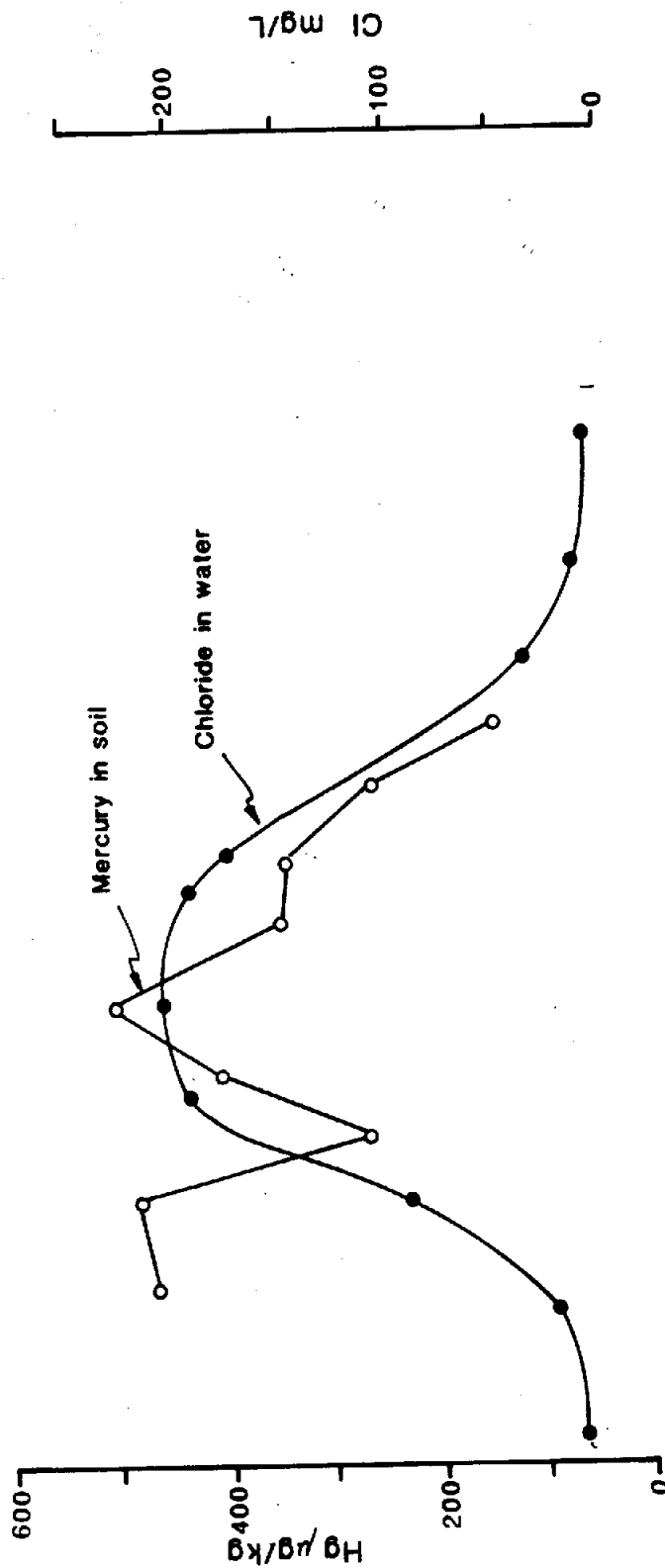


Figure 15. Mercury, chloride and topographic profiles of line E'-E''.

associative magmatic bodies. Because the overall skew of mercury data and the intensity of the gravitational lows are more dominant toward the southwest, the mercury values and the gravitational low northeast of the axis of the valley floor probably represent a lower influx of mercury-charged thermal groundwater into the main Calistoga geothermal reservoir.

#### D. CONCLUSION

Gravity data coupled with soil mercury indicate a dominant fracture flow recharge system and/or magmatic body supplying thermally-recharged water from the southwest into the alluvial deposits of the upper Napa Valley. Degassing of mercury-charged geothermal water probably occurs through minor fissures in the bedrock, while providing a relatively impermeable barrier to inflow of geothermal water. The geothermal water enters into the major bedrock fissure along the axis of the valley and degasses the remaining mercury from the geothermal water while upwelling in the alluvial basinal deposits. A secondary influx of mercury-charged geothermal water enters from the northeastern borderland and is identified by elevated levels of indicator chemicals (i.e. chloride, boron) and mercury levels in soil.

As upwelling geothermal fluid interacts with the alluvial aquifer, it cools and forms a mushroom-shaped plume, with the hot water rising and cool water descending. Along the borders of this geothermal plume during wintertime recharge, fresh, non-thermal water interacts with the thermal water, decreasing the temperature and lowering the chloride and boron content, while increasing iron, sulfate, and the potentiometric head of the bordering groundwater. In the zone of intensive mid-axis thermal upwelling, the seasonal variations of bordering groundwater recharge do not appreciably affect the chemical character of potentiometric surface of the geothermal system. Dominant groundwater flow is downvalley with influxing water from the borderlands and upwelling geothermal fluid contributing to basinal alluvial recharge.

## V. GEOCHEMISTRY

### A. INTRODUCTION

In the initial assessment of geothermal systems, geochemical investigations of subsurface and surface waters can supply information on the following:

- 1) the range in compositions and homogeneity of the hot fluids;
- 2) the type of system present, i.e. steam-heated or hot chloride water;
- 3) zones of high upflow permeability;
- 4) the subsurface rocks associated with the hot fluids;
- 5) subsurface fluid temperatures; and
- 6) the origin of the hot fluids, and the residence time of water in the system.

The majority of known geothermal areas have near-boiling temperatures, which discharge neutral pH or slightly alkaline sodium chloride waters. Chloride is thus an important chemical tracer. Water containing alkali halides is heated to steam and subsequently circulated within the hydrothermal groundwater system, and upon condensation at or near the surface yields sodium chloride water (Faye, 1971). In some areas the chloride concentrations in near-neutral-pH boiling springs are rather low (<100 ppm); for example, about 40 ppm at Beowawe Geysers, Nevada and Carboli, Italy. Nevertheless these compositions are still considerably higher than those found in local surface waters.

Since water compositions vary widely, the type of system may not always be clear. Discharges from wells of 300 feet deep or more may be necessary to determine the character of the local geothermal fluids. In general, however, thermal well water with high-chloride values implies a subsurface liquid-dominated reservoir, while the absence of chloride typically denotes a steam reservoir at depth. Care must be taken, however, in the interpretation of chloride values because several notable exceptions do exist. Also, near-surface rocks can give rise to moderate concentrations of chloride in spring waters; thus knowledge of the near-surface stratigraphy is essential.

In most low-to moderate-temperature geothermal areas dominated by sodium chloride waters, the deep hot water in the center of an area is often characterized by the highest chloride concentrations. A map of isochloride contours in a geothermal area, therefore, may show very accurately the position of the deep-water source, the extent of dilution of hot water rising to the surface, and possibly the boundary of the hot water area. Lower chloride concentrations near the edge of a field often follow the resistivity contours and illustrate progressively greater influxes of fresh water, diluting the chloride content.

The highest chloride concentrations imply the probable upwelling of thermal fluids from depth and indicate permeable zones from deep levels to the surface. Other soluble constituents such as boron and fluoride may also be used in association with chloride to determine whether the system contains one or several hot water aquifers. The use of Cl/B, for example, overcomes dilution and evaporation effects which may mask the lateral distribution of a hot-water system.

Water chemistry also gives information about the nature of the rocks contracting the deep hot waters. High boron, ammonia, iodide, bicarbonate, and carbon dioxide concentrations and low Cl/B ratios often indicate the presence of sedimentary rocks. Anomalously high concentrations of other ions, such as sodium may indicate siliceous volcanic rocks.

En route to the surface, the hot water undergoes dilution and reaction with rock. In estimating deep temperatures, near-boiling point springs or wells of large flow and with near-neutral-pH water should be chosen. The estimates of underground temperatures are generally minimum values. Fournier and Truesdell (1973) and Truesdell and Fournier (1975) developed improved methods of calculating deep temperatures and hot water fractions for mixed and diluted springs that issue at boiling temperatures.

A survey of the hydrogen and oxygen isotope ratios in well waters and local surface water will indicate the recharge area for the geothermal system. A knowledge of the recharge rainfall enables the long-term output capacity of the system to be estimated. Determination of the tritium concentration in the least-diluted well water or in local surface water allows the residence time or flow-time of the hot waters to be assessed.

Finally the use of volatile constituents such as mercury, radon or boron in the soil above a reservoir can be used to effectively define possible geothermal flow patterns. The concentrations of mercury is generally found to be particularly high in thermal waters. Mercury vapor rises upward and away from the zone of thermal upwelling and is subsequently trapped in the soil column overlying active and ancient geothermal areas. The contouring of soil mercury content may therefore also provide an indication of local thermal upwelling.

## B. ANALYTICAL RESULTS AND INTERPRETATION

The Calistoga geothermal area contains a shallow, moderate-temperature resource located at the head of the Napa Valley. Common lithologies through which the meteoric and thermal water passes are graywacke sandstones and siliceous volcanoclastic deposits. Measured surface water temperatures in water wells range from 25°C to 140°C with an average depth of 85 meters. Chemical data from 140 well sites in and around the Calistoga area were compiled by Youngs and others (1980) and supplemented during this study. Water wells in and around the Calistoga area used in this study are shown in Figure 16. Chemical analyses of water from these sites are tabulated in Table 1.

Water chemistry in the Calistoga area has been used to distinguish between waters of a geothermal or nongeothermal origin, or the geothermal component of water in wells of a mixed origin. All geothermal waters analyzed in this study were classified as sodium chloride type and can be easily distinguished by concentration ranges of B (>8 ppm), Cl (>180 ppm), F (>7 ppm), and Na (>170 ppm). The unusually high sodium content is undoubtedly derived from the hydrothermal alteration of feldspar minerals (sodium silicates) and volcanic glass

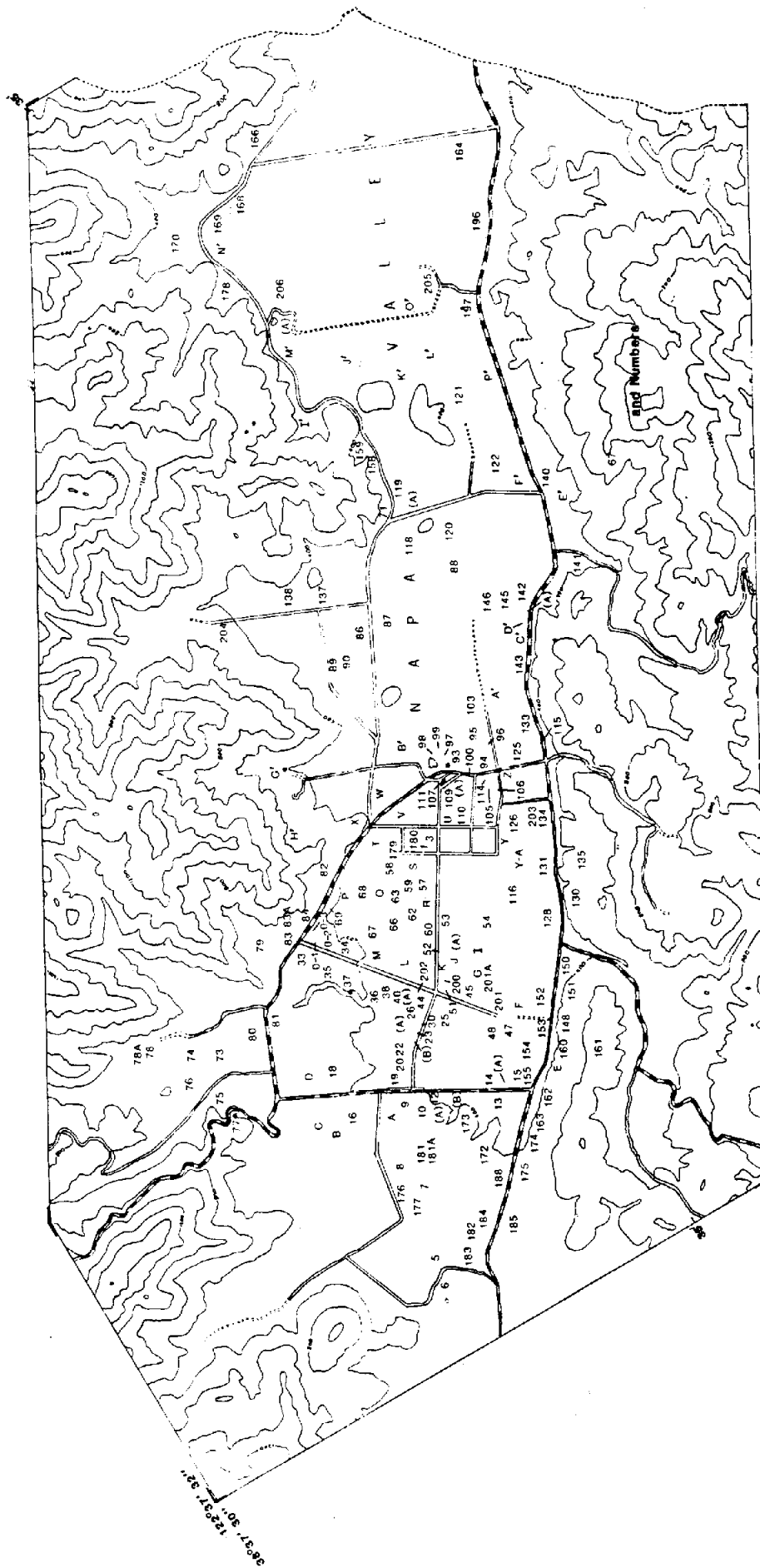


Figure 16. Location map of sampled water wells in the Upper Napa Valley.

TABLE 1 CHEMISTRY OF SELECTED WELLS IN THE CALISTOGA AREA

Sample No.	(feet)				Temp. °C/°F	pH	Spec. Cond. µmho/cm	(ppm)																							
	Well Depth	Water Level		ASL				TDS	CTDS	Na	K	Ca	Mg	Si	Li	B	Fe	Sr	Mn	Cu	Zn	As	Cl	F	SO <sub>4</sub>	HCO <sub>3</sub>					
		Surface	Below Surface																												
G-001-80	300	--	--	45/113	7.0	600	659	586	198	8.0	5.0	1.0	55	1.58	9.7	0.07	0.04	<	<	<	<	202	10.5	--	147.9						
G-003-80	140	15	353	31/88	5.8	380	345	262	57	3.0	19.0	8.0	23	<	0.4	<	0.06	<	<	<	7	0.3	<	169.0							
G-005-80	40	19	406	19/66	6.1	300	446	325	93	3.0	15.0	6.0	32	<	<	0.56	0.10	0.3	<	<	0.3	<	22.0	246.0							
G-007-80	55	7	415	18/64	5.8	245	221	159	11	<	18.0	20.0	13	<	<	<	0.09	<	<	<	10	<	<	126.0							
G-008-80	180	27	399	25/77	6.2	500	527	422	111	7.0	22.0	11.0	12	0.12	6.1	1.04	0.17	<	<	<	0.3	<	111	1.4	10.0	214.0					
G-009-80	190	--	--	135/275	8.5	1150	518	--	206	9.0	2.0	<0.5	56	1.95	9.8	<	0.06	<	<	<	<	<	201	11.5	--	--					
G-012-80	250	+0.5	398	65/149	7.2	600	654	580	202	7.0	2.0	<0.5	61	1.81	9.4	0.08	0.02	<	<	<	--	--	190	11.0	<	151.0					
G-012A-80	15	7.5	390	--	--	--	--	--	--	--	--	--	--	--	0.8	--	--	--	--	--	--	--	--	--	--						
G-012B-80	29	--	--	--	--	--	--	--	--	--	--	--	--	--	3.9	0.36	0.13	0.3	<	<	--	--	--	--	--						
G-014-80	55	11	379	15/59	6.35	490	475	366	67	<	26.0	33.0	17	<	<	<	<	<	<	<	<	69	0.3	15.0	220.0						
G-014A-80	150	11	379	--	--	--	--	--	--	--	--	--	--	--	10.2	--	--	--	--	--	--	--	--	--	--						
G-015-80	70	10	373	20/68	6.7	500	445	326	29	<	29.0	36.0	18	<	0.8	7.27	0.15	1.7	<	<	<	69	0.2	<	236.0						
G-016-80	400	8	412	37/99	6.5	980	662	567	184	4.0	28.0	2.0	20	1.12	9.8	0.56	0.10	<	<	<	<	190	8.5	<	194.0						
G-018-80	180	12	396	20/68	7.0	790	641	534	165	<	30.0	0.0	19	0.23	9.3	0.53	0.11	<	<	<	0.2	<	171	5.5	<	217.0					
G-019-80	100	<2	332	64/147	7.4	1200	646	558	190	6.0	5.0	<0.5	54	1.99	7.4	<	0.03	<	<	<	<	<	156	9.5	16.0	179.0					
G-020-80	193	--	--	98/208	7.25	1220	675	599	190	7.0	30.0	1.0	60	2.05	9.9	0.08	0.06	<	<	<	0.6	<	201	11.0	<	165.0					
G-022-80	153	<2	392	47/117	7.3	1070	673	594	185	9.0	14.0	1.0	75	1.78	9.6	0.31	0.03	<	<	<	0.5	<	187	11.0	<	159.0					
G-023-80	24	15	372	19/66	6.75	142	236	194	5	<	86.0	13.0	9	<	<	0.20	0.11	<	0.1	3.1	<	7	<	13.0	85.0						
G-023A-80	240	+1.5	392	63/145	7.9	--	610	--	170	8.4	--	--	--	--	10.0	--	--	--	--	--	--	--	--	--	220.0						
G-025-80	200	7	376	61/142	7.0	910	615	557	179	10.0	22.0	4.0	39	1.53	9.9	0.12	0.06	<	<	<	0.7	<	188	9.1	13.0	166.0					
G-037-80	410	7	392	52/108	6.7	1190	645	560	188	7.0	8.0	1.0	31	1.75	10.1	0.21	0.04	<	<	<	<	195	10.0	<	172.0						
G-038-80	200	--	--	17/63	6.1	590	435	354	87	<	20.0	7.0	16	<	5.1	2.39	0.09	<	<	<	3.0	<	92	0.9	13.0	165.0					
G-040-80	140	21	366	15/59	6.55	870	692	584	173	5.0	41.0	9.0	20	0.13	10.9	1.26	0.11	0.4	<	<	1.7	<	186	4.2	<	220.0					
G-044-80	220	--	--	40/104	6.65	1100	678	578	180	12.0	11.0	4.0	35	1.14	10.2	<	0.06	<	<	<	<	<	194	7.0	<	203.0					
G-045-80	195	13	362	24/75	5.9	900	644	551	171	13.0	11.0	6.0	3	1.06	9.8	0.67	0.06	<	<	<	<	<	186	7.1	<	188.0					
G-047-80	65	16	360	15/59	6.0	650	413	320	116	<	17.0	15.0	18	<	7.3	0.31	0.07	<	<	<	0.2	<	132	1.1	<	188.0					
G-048-80	65	14	367	18/64	5.8	720	581	480	103	<	28.0	20.0	17	<	8.1	2.94	0.13	1.1	<	<	<	162	1.4	<	304.0						
G-051-80	35	9	374	13/55	6.1	700	710	604	128	2.5	28.0	13.0	17	<	7.6	0.23	0.14	<	<	<	3.5	<	5.5	22.0	214.0						
G-052-80	60	15	366	19/66	6.25	590	389	319	27	<	66.0	19.0	24	<	0.3	0.04	0.26	<	<	<	2.0	<	38	0.04	49.0	143.0					
G-054-80	190	12	350	24/75	6.9	1050	775	635	203	7.0	18.0	9.0	20	0.59	11.7	0.04	0.09	0.5	<	<	0.2	<	189	0.7	11.0	284.0					
G-057-80	160	25	350	38/100	6.5	1180	797	648	203	5.0	25.0	8.0	29	0.32	8.9	0.12	0.12	0.4	<	<	<	181	2.2	<	303.0						
G-058-80	200	--	--	74/165	6.65	1120	643	561	191	4.0	10.0	1.0	42	1.40	9.4	0.14	0.05	<	<	<	<	191	8.5	<	166.0						
G-062-80	32	15	365	19/66	6.5	495	403	<	318	46	<	39.0	14.0	25	<	0.5	0.34	0.12	<	<	0.3	<	49	0.2	34.0	173.0					
G-068-80	6	65	302	26/79	7.0	800	600	506	152	4.0	12.0	4.0	24	0.49	7.5	0.21	0.04	<	<	<	<	140	4.8	41.0	191.0						
G-071-80	265	90	290	30/86	6.9	1030	746	595	32	7.0	234.0	46.0	11	<	<	4.75	0.51	<	<	<	0.9	<	25	0.3	85.0	327.0					
G-074-80	130	24	416	16/61	6.8	500	429	305	32	<	54.0	16.0	13	<	<	0.64	0.29	<	<	<	0.3	<	8	0.1	30.0	252.0					
G-077-80	240	--	--	19/66	6.8	440	370	275	12	<	51.0	21.0	15	<	<	0.12	0.12	<	<	<	4.0	<	32	--	20.0	193.0					
G-078-80	110	25	420	15/59	7.0	170	244	211	8	<	23.0	5.0	10	<	<	0.21	0.12	<	<	<	0.5	<	6	<	21.0	66.0					
G-078A-80	150	21	427	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--					
G-079-80	120	27	413	21/70	6.8	460	399	282	22	<	57.0	11.0	10	<	<	<	0.14	<	<	<	<	8	0.3	28.0	237.0						
G-080-80	162	27	397	19/66	6.8	148	198	155	15	<	15.0	4.0	12	<	<	0.90	0.10	<	<	<	0.2	<	17	0.1	23.0	86.0					
G-081-80	28	23	401	16/61	7.0	93	161	118	7	<	10.0	3.0	12	<	<	0.43	0.03	<	<	<	<	5	<	<	<						
G-083-80	200	--	--	19/66	6.0	178	212	157	10	<	30.0	7.0	10	<	<	0.68	0.06	<	<	<	0.7	1.0	5	<	13.0	112.0					
G-083A-80	300	--	--	32/90	--	--	--	--	--	--	--	--	--	--	<1.0	--	--	--	--	--	--	--	--	--	--	--					
G-084-80	120	49	391	24/75	6.1	540	443	318	27	<	67.0	17.0	10	<	<	0.36	0.21	<	<	<	0.6	<	28	0.4	16.0	254.0					
G-086-80	125	--	--	24/75	6.4	250	277	199	31	<	22.0	6.0	5	<	0.3	0.07	0.09	<	<	<	1.7	<	15	0.1	15.0	158.0					
G-087-80	55	14	324	18/64	6.05	112	235	210	8	<	119.0	7.0	16	<	<	1.80	0.09	<	<	<	3.0	<	5	1.80	<	51.0					
G-088-80	400	20	402	26/79	6.15	500	492	338	60	<	62.0	13.0	15	<	<	1.27	0.13	0.9	<	<	1.7	<	13	<	<	312.0					
G-089-80	240	55	300	22/72	6.2	135	104	83	11	<	13.0	3.0	12	<	<	0.15	0.06	<	<	<	<	5	<	<	30.0						
G-090-80	120	--	--	20/68	5.8	112	112	97	11	<	11.0	4.0	11	<	--	0.17	0.04	<	<	<	0.2	<	6	0.1							

TABLE 1 Continued

Sample No.	Well Depth	(feet)		Temp. °C/°F	pH	Spec. Cond. Mho/cm	(ppm)																		
		Mater Level	ASL				TDS	CTDS	Na	K	Ca	Mg	Si	Li	B	Fe	Sr	Mn	Cu	Zn	As	Cl	F	SO4	NO3
G-135-BC	440	37	423	19/66	6.5	480	436	345	51	9.0	14.0	7.0	29	0.27	0.3	0.19	0.05	0.4	<	3.3	<	9	0.3	50.0	232.0
G-138-BC	125	35	343	25/77	5.9	265	268	193	33	<	24.0	2.0	21	<	<	0.11	0.05	<	<	0.3	<	6	1.4	14.0	187.0
G-140-BC	200	31	311	16/64	6.7	300	320	226	60	<	4.0	1.0	23	0.06	0.3	1.40	<	<	<	<	<	6	0.3	<	127.0
G-141-BC	212	--	--	23/73	6.9	118	240	176	23	7.0	5.0	4.0	36	<	<	1.33	0.3	0.5	<	<	<	25	0.6	22.0	250.0
G-142-BC	55	19	305	18/64	6.9	449	446	319	72	6.0	11.0	9.0	29	<	0.5	0.67	0.07	1.0	<	<	<	<	<	<	<
G-143-BC	240	Pe	314	22/72	6.9	880	641	501	138	5.0	14.0	6.0	24	<	8.0	1.50	0.08	0.4	<	0.3	<	130	1.2	15.0	275.0
G-145-BC	100	20	305	16/64	6.1	298	276	199	33	<	10.0	7.0	26	<	0.4	0.21	<	<	<	0.3	<	8	0.4	16.0	151.0
G-146-BC	38	15	305	18/64	6.0	218	278	207	25	<	14.0	10.0	32	<	0.07	0.2	0.75	0.08	0.7	<	<	9	0.3	25.0	139.0
G-146-BC	15	15	305	--	7.1	--	--	--	13	--	6.8	3.9	--	--	0.06	0.1	--	0.02	0.01	0.002	1.001	7	0.08	0.6	51.0
G-150-BC	212	30	360	20/68	6.4	650	577	443	107	11.0	15.0	9.0	25	0.27	5.5	1.02	0.09	0.5	<	0.4	<	180	0.3	<	264.0
G-152-BC	120	11	374	20/68	6.1	710	578	442	96	10.0	21.0	13.0	30	0.16	5.4	0.20	0.11	0.8	<	0.2	<	103	0.3	<	256.0
G-153-BC	140	9	373	15/69	6.3	700	549	423	87	6.0	19.0	15.0	30	0.15	5.1	1.13	0.13	<	<	<	<	106	0.4	<	249.0
G-154-BC	400	10	373	18/64	6.2	410	419	297	36	3.0	33.0	12.0	12	<	1.7	<	0.16	<	<	<	37	0.2	16.0	241.0	
G-159-BC	350	70	290	18/64	6.7	630	618	420	16	<	89.0	22.0	9	<	<	3.49	0.66	<	<	0.2	<	33	0.3	<	292.0
G-160-BC	300	18	380	20/68	6.7	400	500	352	69	14.0	18.0	6.0	32	0.10	1.5	2.78	0.09	1.0	<	<	<	7	<	<	<
G-161-BC	430	--	--	35/95	6.8	350	466	370	63	17.0	14.0	3.0	43	0.05	0.2	0.14	<	<	<	0.2	<	6	0.2	<	289.0
G-162-BC	95	11	384	14/57	6.4	360	385	282	36	10.0	17.0	15.0	30	<	<	0.07	0.11	2.5	<	<	17	0.2	33.0	208.0	
G-164-BC	180	22	263	20/68	6.0	155	209	152	8	5.0	10.0	6.0	24	<	<	1.13	0.06	<	<	<	7	<	<	114.0	
G-166-BC	240	80	280	20/68	5.9	1010	629	516	61	3.0	144.0	21.0	16	0.13	<	0.10	0.22	1.2	<	1.1	<	12	0.2	125.0	221.0
G-168-BC	305	--	--	19/66	6.0	115	154	120	8	<	10.0	3.0	12	<	<	1.20	0.04	<	<	2.5	<	7	<	20.0	66.0
G-169-BC	350	--	--	40/104	6.1	370	400	277	54	<	20.0	3.0	22	<	<	<	0.13	<	<	<	<	5	0.3	31.0	243.0
G-170-BC	385	--	--	12/63	6.2	490	473	334	37	<	54.0	10.0	18	<	<	0.05	0.46	<	<	0.3	<	7	0.3	49.0	274.0
G-174-BC	125	15	382	19/66	6.2	450	453	322	61	11.0	13.0	10.0	32	<	0.4	0.83	0.09	1.2	<	0.1	<	23	0.2	26.0	254.0
G-176-BC	52	13	411	18/64	6.5	210	374	263	15	3.0	64.0	15.0	9	<	1.0	0.13	0.32	<	<	1.0	<	6	0.2	19.0	218.0
G-177-BC	122	20	403	18/64	6.7	340	260	183	10	<	16.0	19.0	13	<	<	<	0.09	<	<	<	<	9	0.1	21.0	151.0
G-178-BC	86	--	--	30/86	6.1	--	401	299	38	<	50.0	11.0	23	0.08	<	0.04	0.14	<	<	<	<	15	0.3	39.0	202.0
G-179-BC	213	26	346	85/185	6.45	--	746	649	236	8.0	15.0	2.0	37	1.78	12.7	0.36	0.03	<	0.5	<	194	11	<	207.0	
G-181-BC	151	18	398	20/68	6.0	--	541	430	121	4.0	19.0	18.0	16	0.06	8.3	0.27	0.11	<	<	1.7	<	107	1.7	<	286.0
G-183-BC	90	11	413	18/61	6.2	--	417	290	75	6.0	21.0	4.0	31	<	0.06	1.08	0.06	0.4	<	0.4	<	6	0.2	12.0	241.0
G-185-BC	110	13	402	20/68	6.4	--	589	424	128	15.0	11.0	3.0	38	0.06	0.8	1.23	0.07	<	<	0.3	<	25	0.3	10.0	336.0
G-188-BC	210	14	369	19/66	6.1	--	612	431	114	10.0	19.0	16.0	26	0.08	1.3	0.27	0.12	0.7	<	2.0	<	36	0.3	<	367.0
G-196-BC	200	--	--	19/66	6.2	--	373	257	41	10.0	26.0	8.0	22	<	<	0.06	0.4	<	<	1.6	<	7	0.3	<	236.0
G-197-BC	260	30	275	20/68	6.1	--	310	215	31	10.0	11.0	8.0	29	<	<	0.06	0.9	<	<	<	7	0.4	<	193.0	
G-201-BC	6	205	373	33/91	6.3	--	691	576	173	11.0	13.0	5.0	32	1.20	10.1	<	0.05	<	<	0.3	<	191	7.5	<	230.0
G-204-BC	160	28	392	--	6.4	250	277	199	48	<	98.0	22.0	11	<	<	0.35	<	<	<	1.7	<	13	0.3	17.0	158.0
G-205-BC	240	21	278	23/73	8.35	--	276	169	21	9.0	15.0	9.0	30	0.24	0.3	<	0.13	0.3	<	<	<	29	0.7	12.0	217.0
G-206-BC	240	60	300	55/131	8.19	--	667	549	186	7.0	16.0	2.0	32	1.46	9.8	<	0.23	<	0.1	<	229	10.0	<	153.0	
G-207-BC	14	120	14	390	--	8.0	250	--	--	26	<	38.0	16.0	--	0.9	5.5	--	--	--	--	10	--	13.0	--	
G-208-BC	80	--	--	--	--	--	--	--	--	38	<	260.0	10.0	--	0.25	--	--	--	--	--	12	--	16.0	--	
G-209-BC	440	29	376	44/112	8.3	240	--	--	--	28	<	38.0	20.0	--	0.8	0.2	--	--	--	--	10	--	9.0	--	
A-B4	81	+0.5	416	--	--	--	--	--	--	--	--	--	--	--	<1.0	--	--	--	--	--	--	--	--	--	--
B-B4	112	6	405	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
C-B4	100	7	408	--	7.5	330	240	--	16	--	30.0	11.0	--	--	0.05	0.79	--	0.15	--	--	3.3	--	40.0	160.0	
D-B4	--	25	390	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
E-B4	146	15	375	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
G-B4 (Arroyo-1)	205	--	--	25/77	6.8	550	660	556	168	9.0	11.0	7.0	26	0.77	10.4	0.21	0.08	0.6	<	<	191	7.5	<	212.0	
I-B4	143	14	356	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
J-B4	200	11	369	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
K-B4 (Arroyo-2)	885	45	337	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
M-004-BC (120')	--	--	--	33/91	7.1	790	678	580	174	8.0	16.0	6.0	15	0.50	10.2	2.79	0.08	<	<	--	183	6.5	<	200.0	
M-005-BC (240')	--	--	--	33/91	7.1	830	668	563	166	7.0	15.0	7.0	13	0.54	10.3	3.05	0.08	0.3	<	<	175	5.8	--	212.0	
M-015-BC (320')	--	--	--	38/100	7.65	800	680	587	183	5.0	7.0	2.0	54	1.39	11.5	5.01	0.05	<	<	6	188	9.0	<	189.0	
M-010-BC (620')	--	--	--	51/124	7.9	820	730	623	204	6.0	8.0	1.0	36	1.18	12.6	8.78	0.07	<	<	0.3	--	189	7.3	<	217.0
L-B4	80	19	361	--	--	--	--	--	--	--	--	--	--	--	8.3	--	--	--	--	--	--	--	--	--	--
M-B4 (Moore-1)	562	--	--	--	--	--	--	--	--	--	--	--	--	--	<1.0	--	--	--	--	--	--	--	--	--	--
M-016-BC (12')	--	--	--	12/54	7.75	122	182	145	13	<	22.0	<	36	<	0.2	0.11	0.07	<	<	2.2	<	7	<	11.0	75.0
M-018-BC (210')	--	--	--	36/99	8.4	880	651	549	170	4.0	14.0	4.0	30	0.60	11.2	0.32	0.06	<	0.1	--	188	4.3	<	207.0	
M-020-BC (1282')	--	--	--	46/115	8.4	850	652	564	174	5.0	23.0	3.0	34	0.86	10.9	2.05	0.08	<	1.0	--	189	6.0	<	179.0	
M-023-BC (562')	--	--	--	61/142	8.4	950	668	608	184	7.0	8.0	1.0	34	1.68	10.5	2.31	0.06	<	0.3	--	260	11.2	<	122.0	
P-B4	125	14	383	--	--	--	--	--	--	--	--	--	--	--	<1.0	--	--	--	--	--	--	--	--	--	--
R-B4	180	11	367	--	--	--	--	--	--	--	--	--	--	--	5.3	--	--	--	--	--	--	--	--	--	--
S-B4	280	30	347	66/150	--	--	--	--	--	--	--	--	--	--	<1.0	--	--	--	--	--	--	--	--	--	--
T-B4	85	10	366	--	--	--	--	--	--	--	--	--	--	--	7.8	--	--	--	--	--	--	--	--	--	--
U-B4 (High School)	350	24	335	--</																					

found in the ash-flow tuffs of the Sonoma Volcanics. The feldspar minerals are extremely susceptible to chemical attack and tend to dissociate, yielding the sodium ion to solution. Once in solution, sodium combines readily with aluminum to form a series of clay minerals such as kaolinite, illite and montmorillonite, the typical clays found intercalated with volcanic ash during drilling.

Freshwater, on the other hand, is characterized as bicarbonate type with relatively high concentrations of  $\text{SO}_4$ , Mg and Fe.

The ratio Cl/B has been useful in further distinguishing between geothermal and nongeothermal waters in a particular area (Ellis, 1970; Hull and Elders, 1984). Since boron and chloride act as soluble elements which are not controlled by temperature and pressure-dependent chemical equilibria, these ions will have a constant Cl/B ratio in waters of a geothermal origin, while waters of a nongeothermal origin tend to be more variable. Mixed waters also have characteristic water chemistries, but depend upon the relative contributions of each component end-member. Figure 17 displays the molecular proportions of chloride, boron, and bicarbonate in a range of waters from the Calistoga area. The homogeneity of the geothermal water is evident; the hottest wells have analyses which plot at the low  $\text{HCO}_3$  end of the constant Cl/Bx10 lines. The close grouping of points along the 6.25 Cl/Bx10 line is suggestive of a single aquifer, or a source that is chemically very homogeneous. The minor scattering of points about the 6.25 Cl/Bx10 line indicates local contamination (Murray and others, 1985). Of all the wells evaluated in the greater Calistoga area, those with the highest concentrations of chloride and boron are located along the geographic axis of the Napa Valley (Figs. 18 and 19). These wells also display the highest temperatures, as shown in Figure 20, in which water temperatures at a depth of 200 feet below the surface have been contoured to outline the hot water anomaly. Figure 21 clearly illustrates the relationship between temperature and chloride in water wells in the greater Calistoga area. This association between geothermal fluids, chloride and boron, has been noted, and successfully used elsewhere in California to locate faults and to trace thermal waters transported upward along these shear zones (Barnes, 1970; Hall and Elders, 1984).

The elongated chloride contours parallel the valley axis, and the near-constant chloride concentrations along the mid-valley trend suggests a linear source for the upwelling thermal water. The proximal location of water wells displaying the highest TDS along this mid-valley trend (ranging from 600 to 900 ppm) also supports a linear source for the thermal water. These moderately-high mineralized waters, characteristic of upwelling geothermal fluids, are found in the same wells with chloride values ranging from 183 to 229 ppm, boron values of 8 to 10 ppm, fluoride concentrations ranging from 7 to 12 ppm and subsurface temperatures in excess of 100°F (Table 1). Combining the zones of anomalously high chloride, boron, and temperature values onto a single composite diagram (Fig. 22) provides a two-dimensional view of the upwelling and localization of the thermal fluids in the greater Calistoga area. The decrease in values toward the margins of the valley, away from the valley axis, suggests that thermal upwelling is occurring along a buried fault or fracture zone which acts as a conduit for the upward migration of fluids.

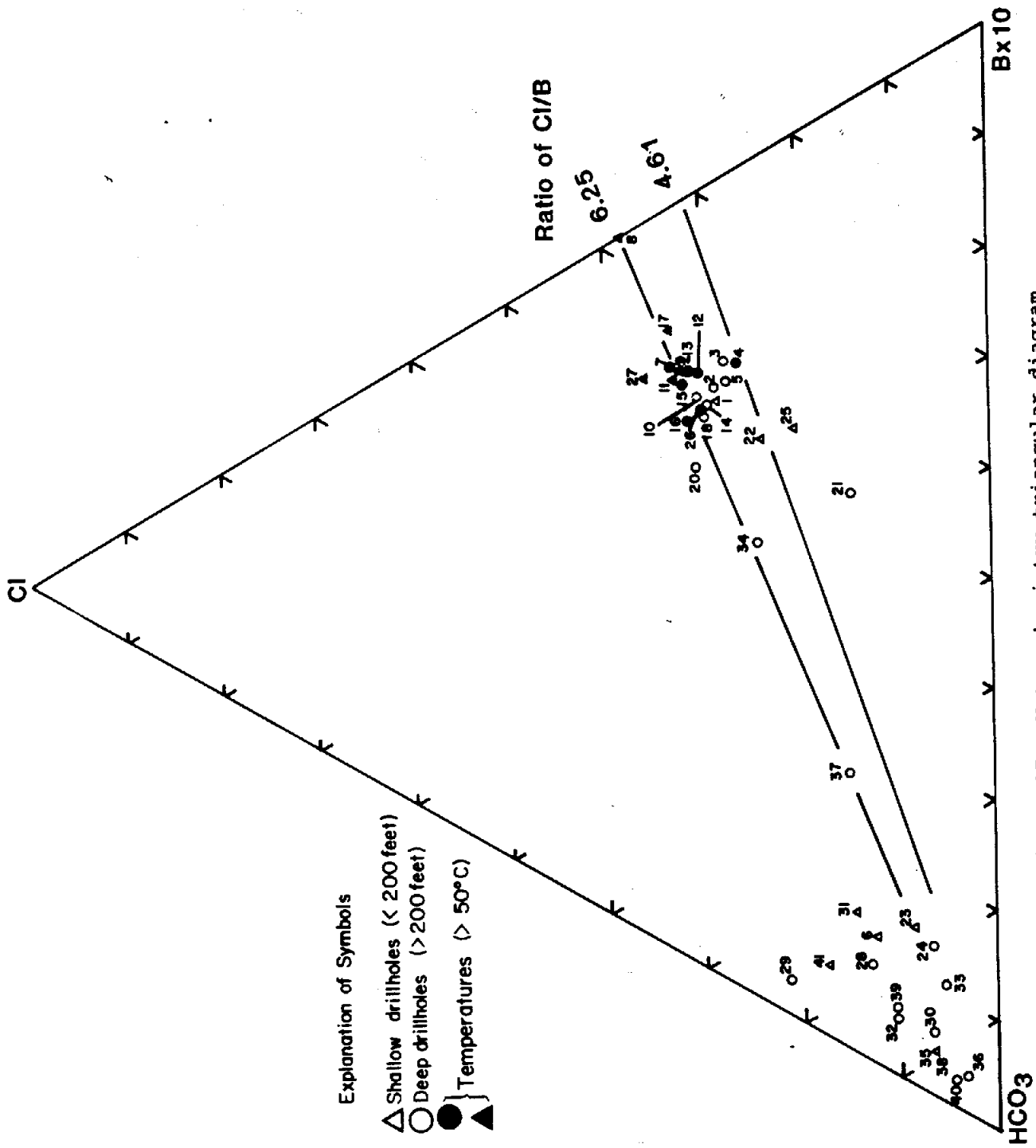


Figure 17. Water chemistry triangular diagram.

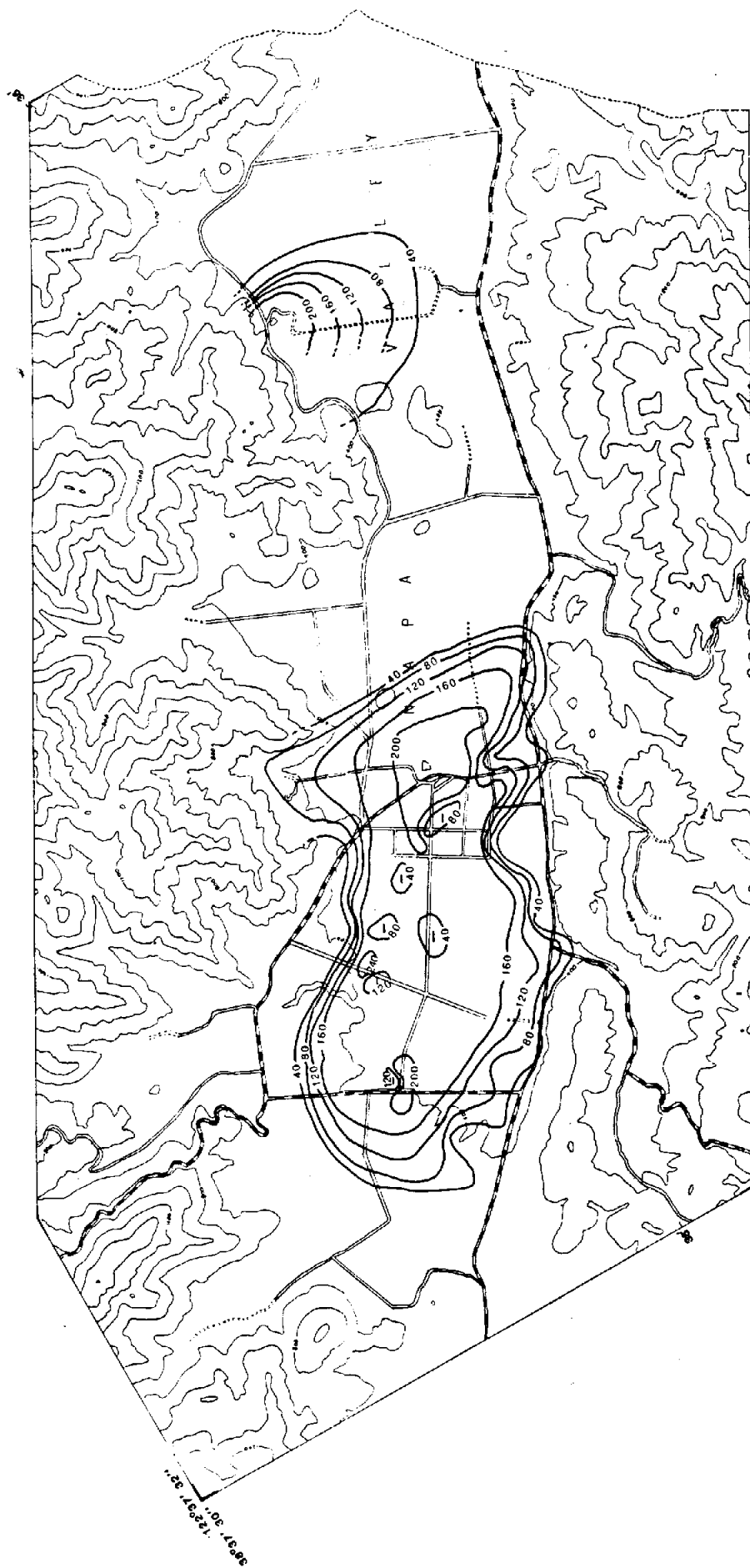


Figure 18. Isochloride concentrations map.

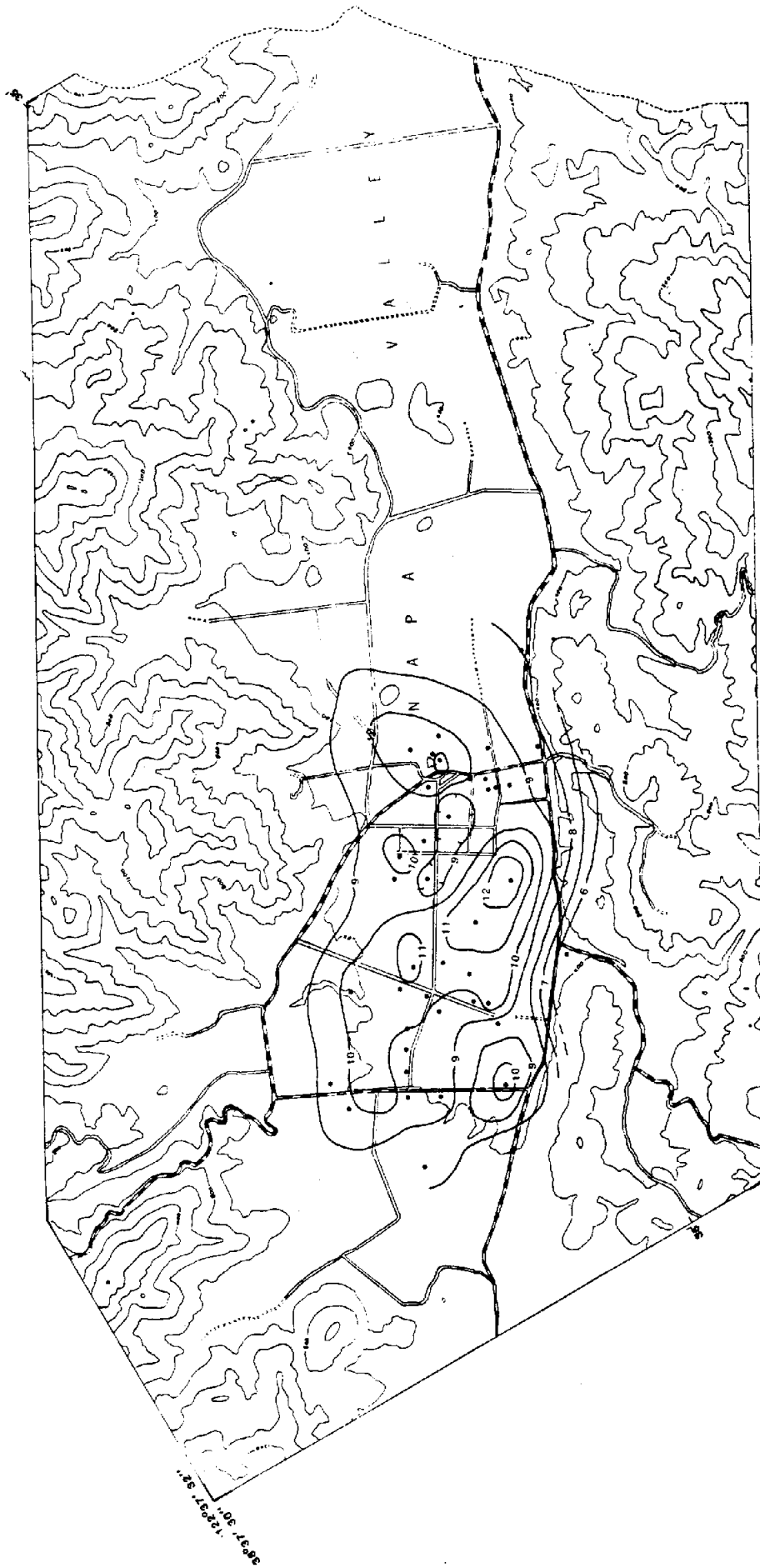


Figure 19. Isoboron concentration map.

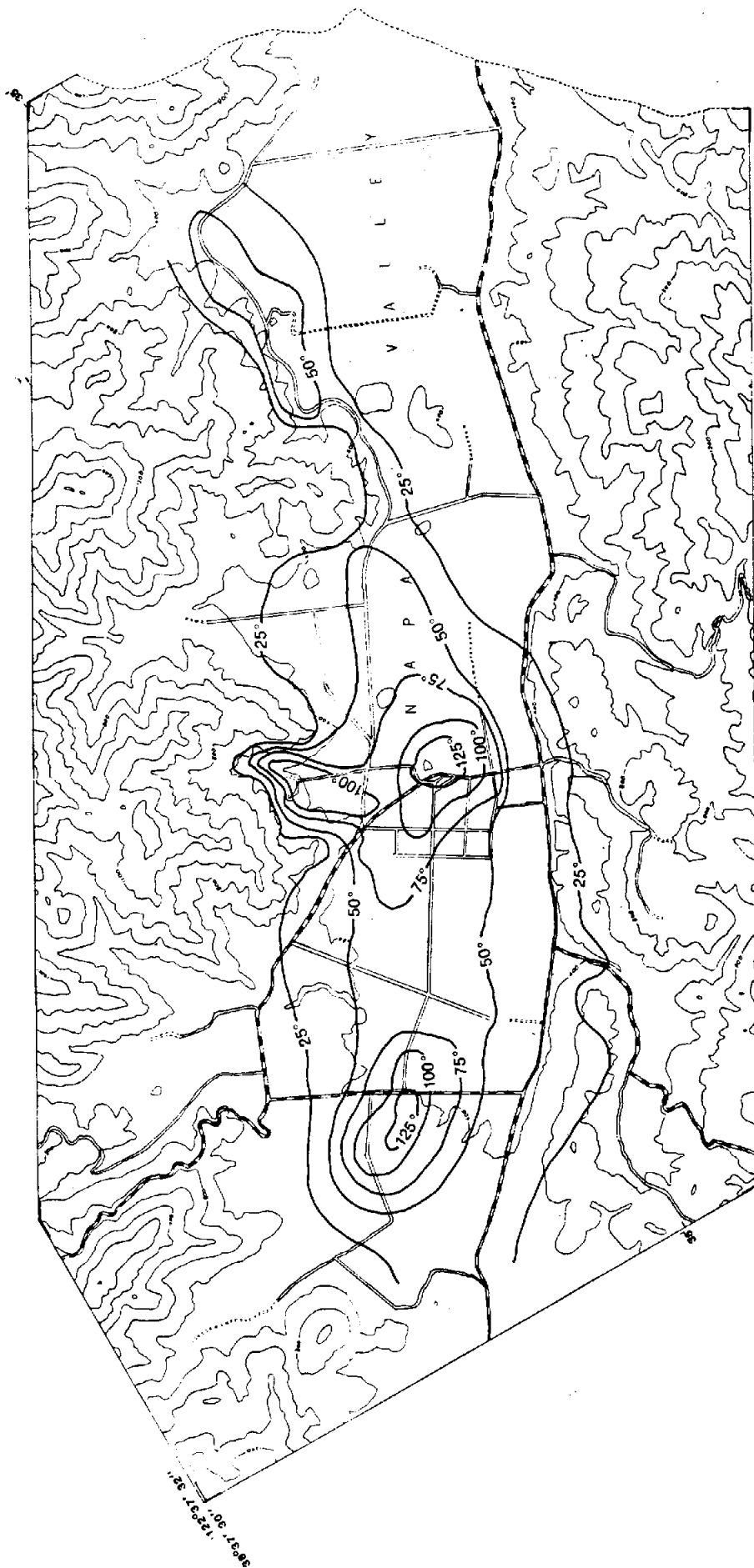


Figure 20. Isothermal map of water temperatures from wells 200 to 300 feet deep.

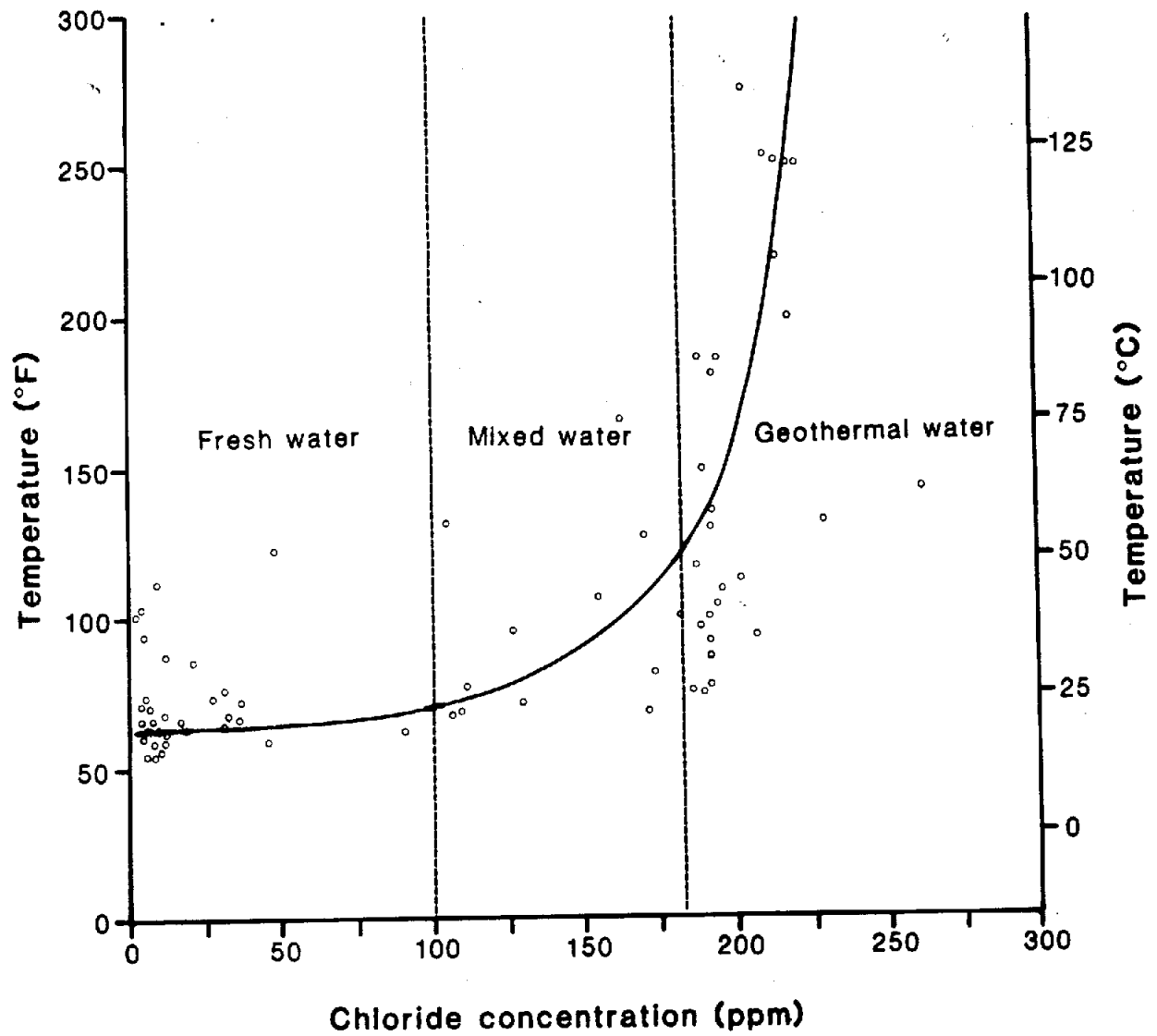


Figure 21. Graph of chloride concentration versus temperature.

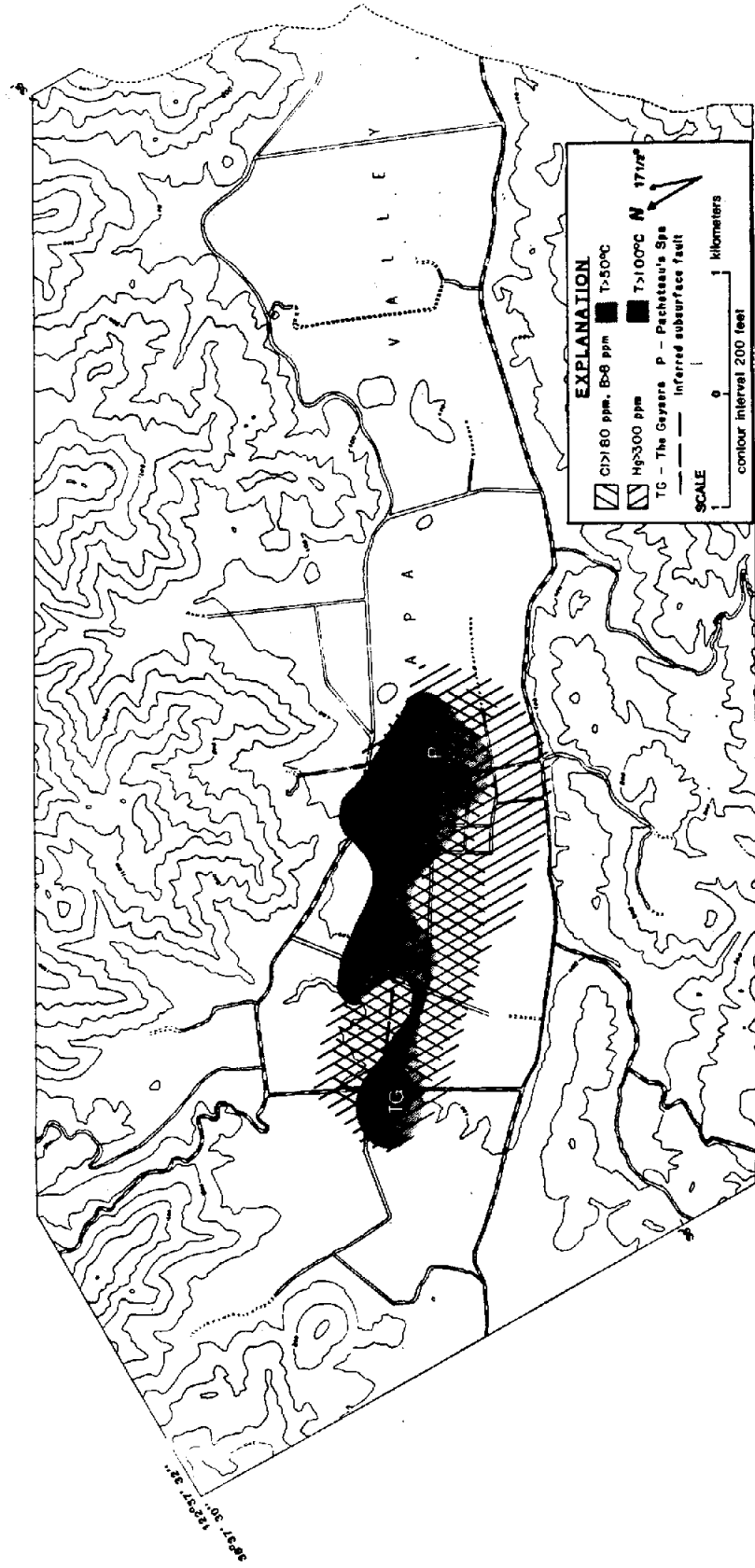


Figure 22. Composite map of chloride, boron, soil mercury and temperature anomalies.

This "fault-charged" model for the Calistoga geothermal resource, where one or more major faults provides most of the energy to the geothermal reservoir, has been proposed by Waring (1915), Youngs and others (1980) and is supported by regional structural analysis and geophysical exploration (Youngs and others, 1981). Inspection of the soil mercury contour map (Fig. 9) also shows a similar linear relationship as indicated in Figures 18 through 20, and 22, and further supports the existence of a fracture system located along the geographic axis of the valley. Such a fault-charged model also helps to explain the localized rise in the potentiometric surface near the Geyser and at Pacheteau's Spa. The selective upwelling of thermal water along the fracture or fault conduit as the geothermal system is recharged causes the water-level in wells located near the fault to rise (Fig. 5).

The decrease in chloride content, Mercury values, and TDS along with a general decrease in temperature and pH away from the valley axis, can be explained by the mixing of hot mineralized water with cool meteoric waters. Fournier (1976) indicates that the composition of a mixed water is likely to exhibit marked non-equilibrium between water and rock. High temperature, high chloride, mid-valley waters are thus compared in Figure 23 to lower temperature waters from the northeast and southwest border of the valley. The proportions of cations and anions in the groundwater from a variety of wells in the upper Napa Valley exhibit three distinct water types when plotted on a trilinear diagram (Piper, 1953). Water from the southwestern border areas of the valley can be easily distinguished from mid-valley waters by more variable but generally lower chloride compositions, and increased  $\text{HCO}_3$ ,  $\text{SO}_4$  and Fe concentrations. Water from the northeastern border areas, as typified by wells 5, 27 and 28 are even lower in chloride with higher concentrations of Ca and Mg. Well 7, plotting within the mid-valley high-chloride range most likely represents the true chemical characteristics of the deeper geothermal aquifer. This water is high in Cl (201 ppm), B (9.8 ppm) and F (11.5 ppm) and low in Fe (0 ppm),  $\text{SO}_4$  (0 ppm) and Mg (0.5 ppm). The scatter associated with the remainder of the analyses, plotting within the sodium chloride-type range, probably reflects minor mixing with surface waters.

#### C. CHEMICAL GEOTHERMOMETRY

##### Introduction

Chemical geothermometry utilizes the composition of waters at well point to estimate temperatures within the hydrothermal system from data on the solubilities and exchange reactions of various solid phases. This hydrochemical method facilitates identification of thermal anomalies of regional and local extent. The basic theory of geothermometry is that chemical equilibria between alteration minerals and solution is attained in geothermal systems for all major components, except chloride (Arnorsson, 1983). In contrast, activities of chloride, fluoride and boron appear to be governed by their rate of leaching from the wall rock. Chemical equilibrium variables include temperature pressure and mobility. Of these, temperature is the dominant factor determining the composition of solvents and solutes. The two main types of temperature-dependent reactions are silica solubilities (geothermometers 1-5, Tables 2 and 3) and sodium, potassium, calcium, magnesium ion

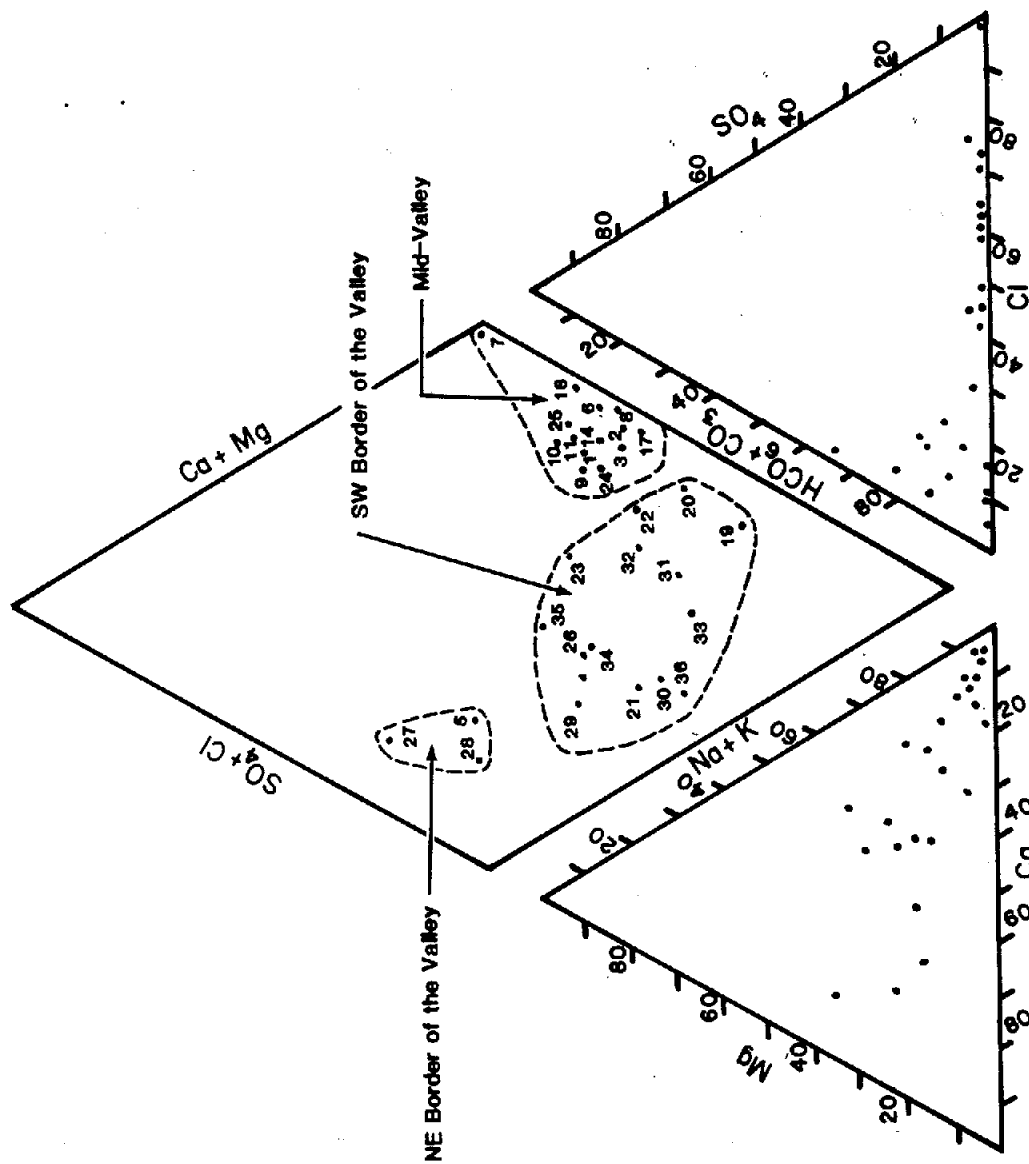


Figure 23. Well water chemistry comparisons for the Upper Napa Valley.

Sample Number	Sampling temp.	Crist. (1)	Chalcedony (2)	Quartz (4) (5)	t°C					w/ dm <sup>g</sup> (11)	(11')	Na-Li (12)			
					Na - K (6) (7)	Na - K - Ca (8) (8') (9)	(10)								
M-002-80	26°C	37	58	64	87	90	209	185	180	138	67	202	50	50	213
M-004-80	33	4	25	33	53	60	158	127	144	104	66	158	47	53	143
M-015-81	38	55	77	81	105	106	126	92	128	107	75	132	66	69	232
M-010-81	51	37	58	64	87	90	131	96	131	112	75	135	108	106	204
M-018-81	36	30	51	57	79	83	118	83	116	82	69	123	59	69	159
G-001-80	91	56	78	81	106	106	150	118	149	137	78	154	102	100	238
G-009-81	135	57	79	82	107	107	155	122	161	173	85	159	-	-	257
G-012-80	81	61	83	85	111	111	140	107	149	160	85	146	-	-	251
G-016-80	37	14	35	42	63	69	114	78	109	68	65	119	-	-	208
G-020-80	116	60	82	85	110	110	144	111	131	85	64	145	-	-	274
G-025-80	61	60	62	67	91	93	172	142	151	104	65	169	82	84	245
G-037-80	52	31	52	58	81	84	145	112	141	117	74	148	112	108	255
G-044-80	40	35	57	62	86	89	185	157	165	131	69	181	60	61	213
G-058-80	74	44	65	70	94	96	112	76	115	91	73	118	106	-	228
G-096-80	85	42	64	69	93	95	134	100	132	106	73	138	-	-	271
G-097-80	95	57	79	82	107	107	157	126	158	156	81	160	-	-	267
G-105-80	44	59	81	84	109	109	141	108	141	126	77	145	-	-	237
G-111-80	104	55	77	80	105	106	155	124	152	137	76	158	-	-	267
G-112-80	30	39	61	66	89	92	130	96	132	115	76	136	85	86	259
G-115-80	35	35	56	61	85	88	188	161	169	137	70	185	52	52	215
G-116-80	41	38	60	65	88	91	131	96	134	121	78	136	55	56	210
G-122-80	15	23	43	50	72	77	246	230	168	57	41	224	36	-	-
G-143-80	27	21	42	48	70	75	143	110	131	87	65	145	27	39	-
G-181-80	20	7	27	35	55	62	137	104	123	72	61	139	-	-	37
G-201-80	64	32	53	59	82	85	181	153	161	121	68	178	52	55	222
G-206-80	55	32	53	59	82	85	145	113	136	96	68	147	103	102	236

Table 2. Calculated subsurface temperatures from selected well waters in the Calistoga area.

Table 3  
Equations for Geothermometers

		<u>Source</u>
(1) Cristobolite	$t^{\circ}\text{C} = \frac{1000}{4.78 - \log \text{SiO}_2} - 273.15$	(1)
(2) Chalcedony	$t^{\circ}\text{C} = \frac{1112}{4.91 - \log \text{SiO}_2} - 273.15$	25-180°C (2) (conductive)
(3)	$t^{\circ}\text{C} = \frac{1264}{5.31 - \log \text{SiO}_2} - 273.15$	100-180°C (2) (adiabatic)
(4) Quartz	$t^{\circ}\text{C} = \frac{1309}{5.19 - \log \text{SiO}_2} - 273.15$	0-250°C (1) (conductive)
(5)	$t^{\circ}\text{C} = \frac{1522}{5.75 - \log \text{SiO}_2} - 273.15$	100-250°C (1)
(6) Na - K	$t^{\circ}\text{C} = \frac{1217}{1.483 + \log (\text{Na/K})} - 273.15$	100-300°C (3)
(7)	$t^{\circ}\text{C} = \frac{933}{0.993 + \log (\text{Na/K})} - 273.15$	25-250°C (1)
(8) Na - K - Ca	$t^{\circ}\text{C} = \frac{1647}{2.24 + \log (\text{Na/K}) + B \log (\sqrt{\text{Ca/Na}})} - 273.15$	4-340°C (4)
	$B = 4/3 \text{ for } \sqrt{\text{Ca/Na}} = 1 \text{ \& } t^{\circ}\text{C} = 100$ $B = 1/3 \text{ for } \sqrt{\text{Ca/Na}} = 1 \text{ \& } t^{\circ}\text{C} = 100$	
(9)	$t^{\circ}\text{C} = \frac{-22200}{\log (\text{Na/K}) - 6.3 \log (\sqrt{\text{Ca/Na}}) - 64.2} - 273.15$	t < 100°C (5)
(10)	$t^{\circ}\text{C} = \frac{1416}{\log (\text{Na/K}) + 0.055 \log (\sqrt{\text{Ca/Na}}) + 1.69} - 273.15$	t > 100°C (5)
(11) Mg correction for Na-K-Ca	$dt_{\text{Mg}}^{\circ}\text{C} = 10.66 - 4.741R + 325.87(\log R)^2$ $-1.032 \times 10^5 (\log R)^2 / T - 1.968 \times 10^7 (\log R)^2 / T^2$ $+1.605 \times 10^7 (\log R)^3 / T^2$	T = K° (6)
	$R = ((\text{Mg}/(\text{K} + \text{Ca} + \text{Mg})) \times 100$ $5 < R < 50$	
(12) Na - Li	$t^{\circ}\text{C} = \frac{1000}{\log (\text{Na/Li}) + 0.38} - 273.15$	(7)

conc. in ppm for eq. (1) thru (7); Molar for eq. (8,9,10,12); equivalents for (11).

sources: (1) Fournier (1977); (2) Arnorson (1983); (3) Fournier (1979); (4) Fournier & Truesdell (1973); (5) Benjamin & others (1983); (6) Fournier & Potter (1979); (7) Fouillac & Michard (1981).

exchange reactions from common hydrothermal alteration mineral assemblages. The process of alteration results in primary minerals being replaced by less dense hydrothermal minerals along with reprecipitation in other sectors of the aquifer. Typical hydrothermal mineral assemblages in low-to-moderate temperature systems include montmorillonite, kaolinite, smectite, low temperature feldspars, chalcedony, quartz and various zeolites (Arnorsson, 1975).

Various assumptions must be understood to fully utilize the values from the geothermometer. Both Fournier and others (1974) and Ellis (1979) have summarized these assumptions:

- (1) Components and species involved in the reaction are sufficiently available.
- (2) The reaction equilibrates within the time that the fluid is present at the depth of interest.
- (3) Little or no reequilibration or change in composition occurs during upflow.
- (4) Mineralized waters coming from depth do not mix with cooler intermediate waters.

Chemical geothermometry assumes specific alteration phases are present in the aquifer. If these phases are not present, the geothermometer will yield anomalous results (Fournier and others, 1974). So, the controlling solubility and exchange reactions must be specified and assumed at depth.

Factors affecting attainment of equilibrium in the reservoir include:

- (1) kinetics of the particular reaction
- (2) the temperature of the reservoir
- (3) the reactivity of the wallrock
- (4) the aqueous concentration of the indicator minerals
- (5) residence time of the water in the reservoir
- (6) homogenization of introduced waters with stored waters

Reequilibration of waters after leaving the depth of interest during flowage to the surface depends on similar factors (Fournier, 1977):

- (1) rate of flow
- (2) path of ascent
- (3) type and reactivity of wallrock traversed
- (4) initial temperature of the reservoir
- (5) kinetics of the various reactions that may occur

Dilution effects should be avoided for accurate deep-reservoir calculations. Ellis (1970), Fournier & Truesdell (1970), and White (1970) have emphasized sampling from wells of highest temperatures and chloride content to provide the most reliable indicators and decrease the possibility of dilution with waters of intermediate to shallow depths. This study centers on waters of high chloride values ( $>180$  ppm) for evaluation of chemical geothermometry.

The temperature of rising fluids may decrease markedly; but, if the fluid in transit rises rapidly, low-reequilibration values may occur and the composition of the emerging waters may reflect the conditions present deeper in the reservoir.

The two main types of reactions controlling chemical geothermometers are solubility and exchange reactions.

#### Data Reduction and Interpretation

Calculated reservoir temperatures from the various geothermometers are presented in Table 2. The sodium-lithium thermometer appears anomalously high and probably should be discarded. The other 12 geothermometers show a wide variance of calculated geothermometry values, spanning a temperature range of approximately 100°C. As a first approximation Figure 24 indicates that some calculated values of principally silica can result in a value lower than the discharge temperature. This possibly indicates a lack of accuracy in this temperature range.

A second approximation however, can be made by separating the geothermometers that indicate low temperatures from the thermometers which indicate higher values. Figure 25 indicates that most of the "low" temperature geothermometers correlate with the general trend of the sampling temperatures. Because of chalcedony's higher rate of kinetics the geothermometer may be indicating intermediate subsurface temperatures. Benjamin (1983) (equation 9, Table 2) calculates values for  $t^{\circ}\text{C}$  less than 100°C by decreasing the value of the feldspar-silica controlling phase and putting greater emphasis on clays and zeolite buffering capacities. Figure 26 compares the calculated values of chalcedony (eq. 2, Table 2) with Benjamin's (1983), (eq. 9, Table 2),  $t$  is less than 100°C, geothermometer. The relationship indicates Na-K-Ca-clay-zeolite values are higher than chalcedony. This could represent a faster kinetic reequilibration rate for chalcedony over the slower sodium-potassium-calcium reaction. A suggested model is that as temperature decreases chalcedony could reequilibrate toward the cooler value while the Na-K-Ca-clay-zeolite reaction remains kinetically slow. At temperatures above 78°C chalcedony's temperature span between its primary heat content and the new cooler value has decreased sufficiently to allow a decrease in the rate of reequilibration. This could provide the mechanism for agreement with the Na-K-Ca-clay-zeolite geothermometer above approximately 78°C. As pointed out by Fournier & Potter (1979), the magnesium-corrected Na-K-Ca geothermometer is sensitive to near surface water rock reactions that occur in response to lower temperatures. These three geothermometers may accurately model intermediate depth, subsurface chemical behavior, while Figure 25 represents the "low" temperature geothermometers, and Figure 27 represents "high" temperature geothermometers. These calculated temperatures show a distinct lack of correlative relationship with sampling temperature and suggest a greater temperature with depth in the reservoir. The sodium-potassium geothermometer (eq. 7, Table 2) groups in the range 90°C to 130°C. Geothermometers (10) & (8) (Table 2) generally indicated temperatures 40°C higher than the Na-K thermometer; however, subsurface lithologic data (discussed in the next section) suggests that the Na-K geothermometer may provide a more accurate indication of subsurface temperatures.

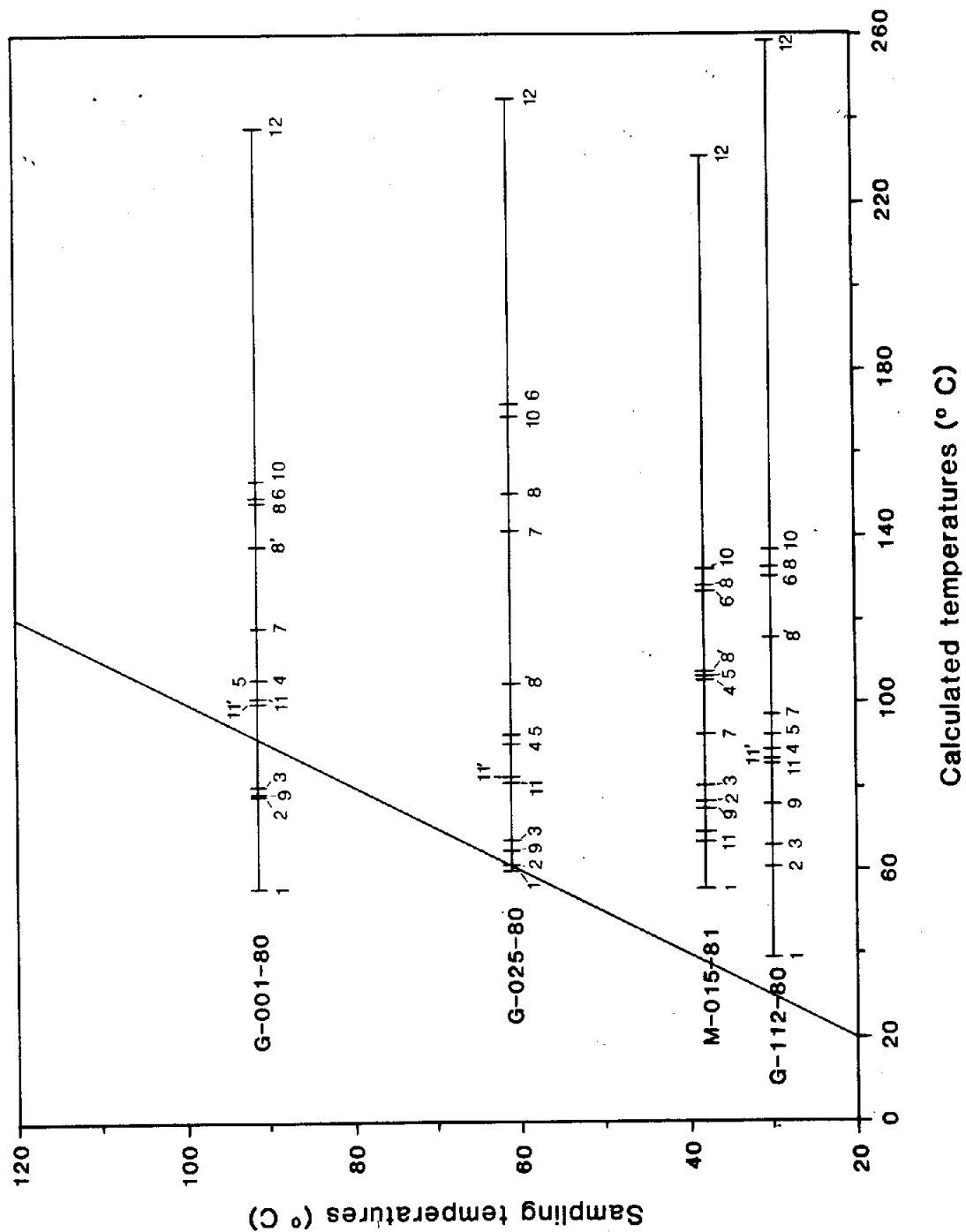


Figure 24. Calculated temperatures for four selected wells.

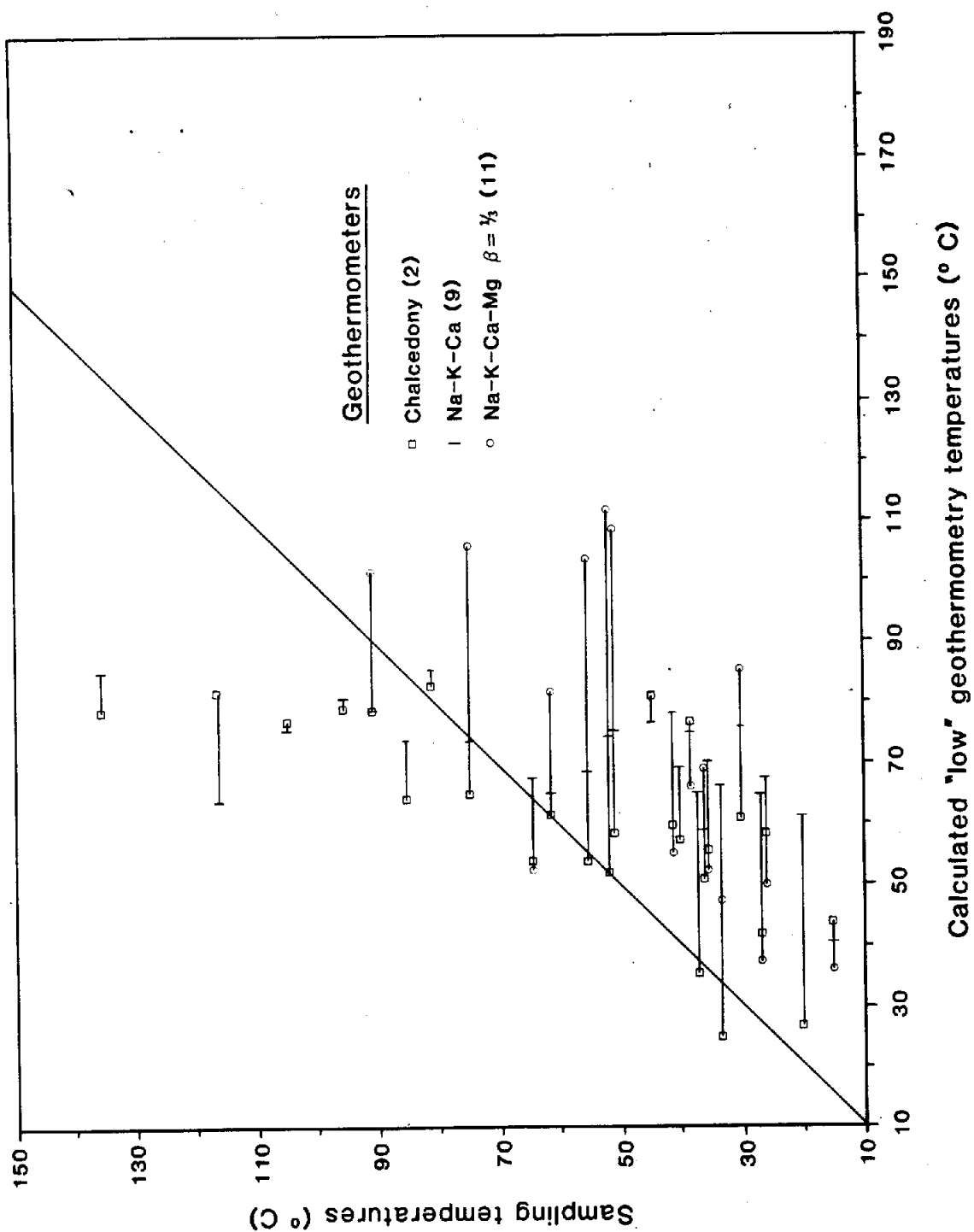


Figure 25. Sampling temperatures versus "low" calculated temperatures.

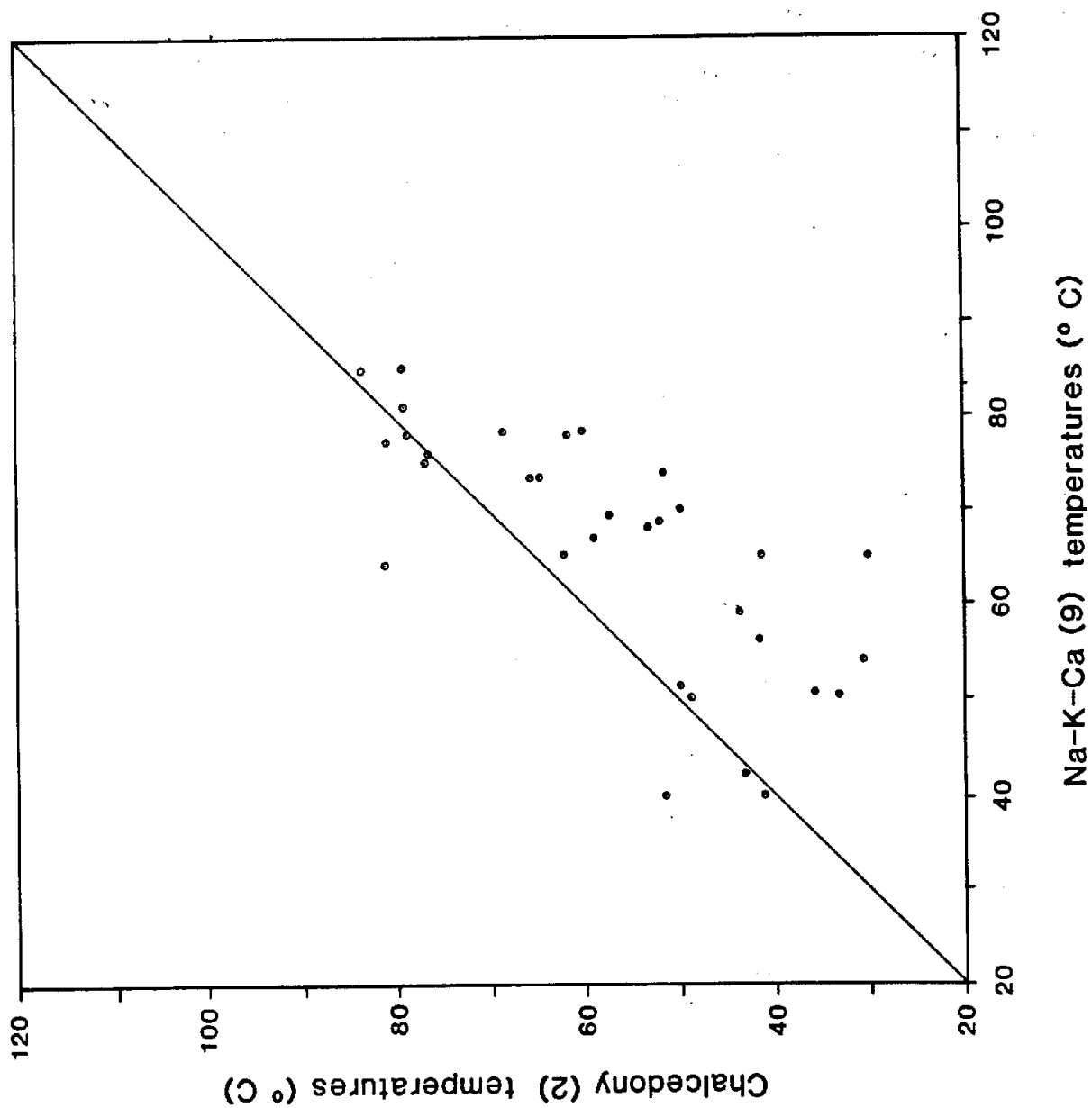


Figure 26. Na-K-Ca versus chalcedony geothermometers.

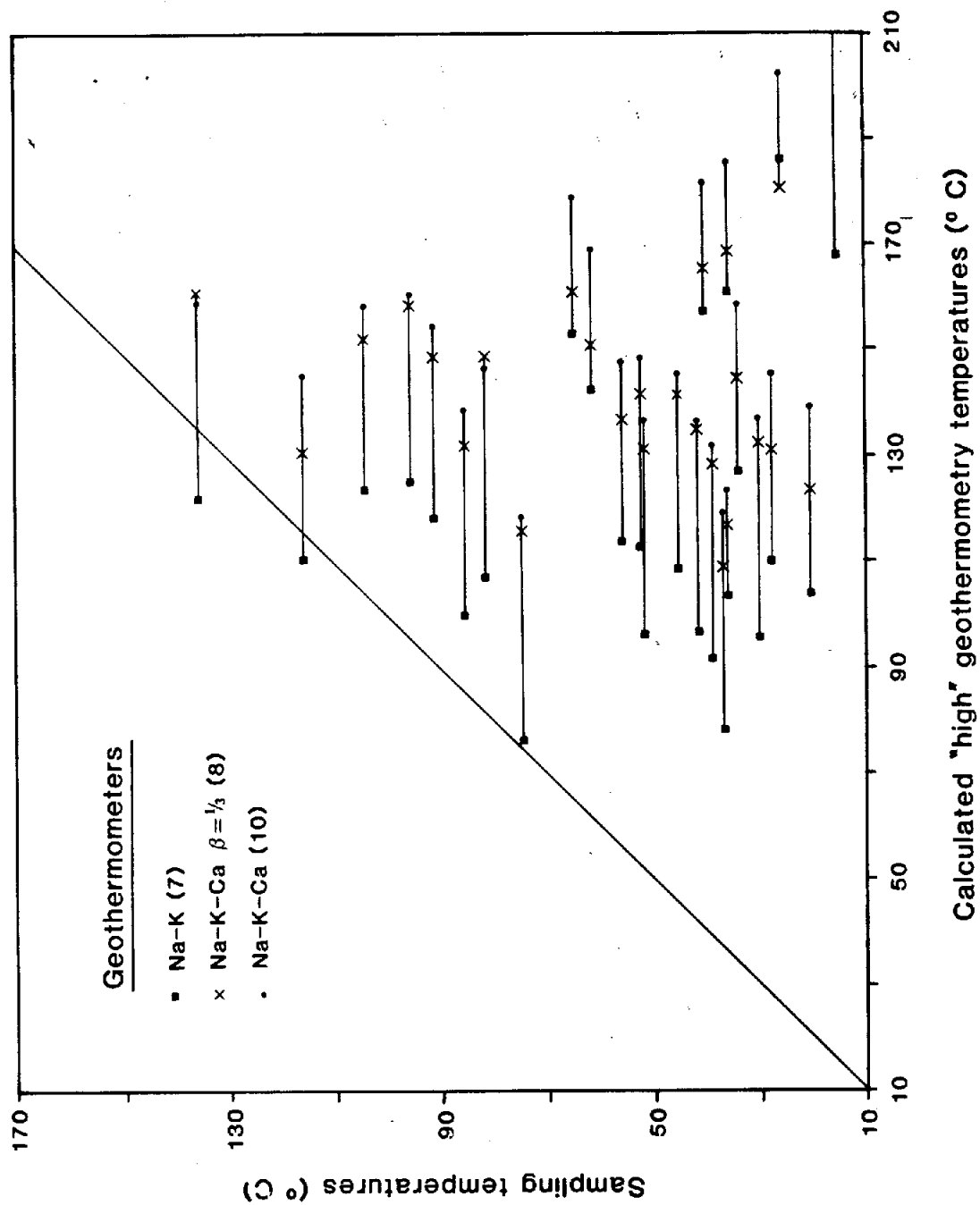


Figure 27. Sampling temperatures versus "high" calculated temperatures.

The liquid-dominated geothermal system in Calistoga shows two regions of elevated subsurface temperatures indicated by chemical geothermometry. Using waters with high ( $\text{Cl} > 180$  ppm) chloride values, a subsurface aquifer of intermediate depth generally registers maximum values approximately  $50^{\circ}\text{C}$  higher than the sampling temperatures registered at shallow depths. A deeper aquifer is indicated to have a similar temperature range perhaps  $100^{\circ}\text{C}$  to  $130^{\circ}\text{C}$ .

#### Summary

The analyses from the Calistoga reservoir indicate that detailed hydrogeological and mineralogical circumstances influence the various geochemical equilibria. This can result in different calculated temperatures with different geothermometers. An uncertainty is associated with the calculations due to the reequilibration of waters with time. Rock type, temperature, kinetics and rate of dissolution appear to be the main factors effecting reequilibration. If these chemical characteristics can be determined, then an overall approximation of subsurface conditions can be more accurately modeled.

#### D. CONCLUSION

The Calistoga Geothermal Field discharges slightly alkaline, sodium chloride-type water at near  $100^{\circ}\text{C}$  from a depth of 100 to 200 feet. Isochloride contour maps were prepared from water well data, and used to determine the location of the upwelling fluids. Soil mercury and boron contour maps were also prepared and used to evaluate subsurface flow patterns and to further define the field boundaries. From this data and exploratory well-drilling data (next section) a fault charged model for the Calistoga Geothermal Field was developed and used to interpret the elongated nature of the zone of upwelling fluids.

Water chemistry data from 140 well sites in the greater Calistoga supports the fault-charged model and indicates mixing of the geothermal fluids with cool, meteoric water toward the margins of the valley. Chemical geothermometry has indicated two regions of elevated subsurface temperatures. Maximum values using the Na-K-Ca geothermometer are  $50^{\circ}\text{C}$  higher than the sampling temperature registered at the surface. The Na-K geothermometer, however, indicates a temperature range of  $90^{\circ}\text{C}$  to  $130^{\circ}\text{C}$  for these regions, and is probably more representative of true reservoir temperatures. Interestingly, chemical geothermometry has also suggested that a deeper aquifer of similar temperature range may exist below the current resource being exploited by the spa and mineral water bottlers. Confirmation of this deeper resource however, must come from deep (800-1,200 feet) temperature gradient (TG) well drilling.

## VI. EXPLORATORY WELL DRILLING

### A. INTRODUCTION

The drilling of test wells in Calistoga was conducted as the final phase in the assessment of the moderate-temperature geothermal resource at Calistoga. A test well-drilling program initiated by the CDMG in 1981 revealed new and unexpected information on subsurface conditions (Taylor, 1981). Significant in this earlier drilling program was the suggestion of multiple aquifers in a vertical section. Each aquifer, apparently separated by thin-to-very-thick layers of moist-to-dry volcanic ash, partly altered to clay. Also important was the finding that basement rocks in many parts of the valley are much deeper than expected and that the configuration of the bedrock surface is apparently highly irregular. A hot water-bearing zone of scoriaceous material underlying a dacitic tuff was encountered in the bottom of two of the three holes drilled. Taylor (1981) has suggested that this zone may provide an as yet untapped deep geothermal resource along the southwestern margin of the Valley. The presence of this deeper resource is also suggested by geothermometry calculations as discussed under the geochemistry section of this report.

Evidence obtained from the CDMG test drilling program has shown that the thickness of the vertical section of sediments that contain, or may contain, geothermal resources was approximately double the conservative estimate published earlier by Youngs and others (1980).

Unfortunately, the CDMG was forced to abandon its test-hole drilling program prior to completion. As a result, extrapolation of drilling results and thus aquifer characteristics to the southeast is tenuous at best. For this reason the CEC, as a part of its resource assessment effort, drilled two additional holes southeast of the CDMG test holes, closer to the downtown commercial business district. In addition, the Roman Spa, located on the corner of Washington and First Street, recently completed a new geothermal well. With permission of Max Quast, owner and proprietor of Roman Spa, CDMG geologist Les Youngs completed a lithologic description of the well during drilling; this information was made available to the author for this study.

Plate 1 represents a correlation of all five CDMG and CEC test holes and the Roman Spa geothermal well. An attempt has been made to accurately portray the subsurface lithology throughout the reservoir area. In addition, temperature gradient logs have been completed on all six holes and have been correlated with other logged wells in two series of temperature gradient cross-section lines trending perpendicular to the valley's axis.

The test holes and the depths drilled by the CDMG and CEC include: Arroyo #1, 205 feet; Arroyo #2, 885 feet; Moore #1, 562 feet; CHS-1, 550 feet; Calis-1, 500 feet; and Roman Spa Well, 265 feet. The locations for the five holes and Roman Spa well are shown in the index map on Plate 1. The vertical lithologic sections for two of the wells as shown on the plate are projected to the cross section line, horizontal distances between adjacent wells as shown on Plate 1 are therefore relative. A brief description of each test hole and the Roman Spa well is summarized in Appendix A.

## B. WATER CHEMISTRY AND TEMPERATURE PROFILES

All aquifers encountered during the drilling of Arroyo #1 and #2, Moore #1 and Calis #1 test holes were sampled, and the water analyzed. Of the 36 chemical analyses taken at various depths from the four drill holes, all water, except in the upper 20 feet, was classified as being of sodium chloride type. Below a depth of 20 feet, levels of boron and chloride increased downward to a depth of approximately 120 feet. Below 120 feet, relatively consistent levels of boron and chloride were obtained, marking the transition to the true geothermal reservoir.

Based on these subsurface investigations, there appears to be a distinct relationship between water quality and depth within the geothermal system. Water quality gradually deteriorates with depth until the geothermal reservoir is reached. Once the geothermal reservoir is penetrated, relatively high yet consistent values of chloride and boron can be expected. Calis 1 (well "Z" on Table 2), illustrates this point quite well. Other wells show similar relationships between water quality and depth. Arroyo #2, for example, also indicates a gradual decrease in water quality with depth until approximately 120 feet. At greater depths, relatively consistent boron values are obtained with only minor fluctuation. Below a depth of 664 feet, for example, boron begins to decrease until the bottom hole depth of 885 feet is reached. The range of boron content for all geothermal water sampled was from 10 to 17 ppm.

It is therefore important to note that within any particular well, there appears to be an adequate vertical connection between adjacent sedimentary layers to allow mixing between the geothermal aquifers and the overlying freshwater. Boron values of greater than 10 ppm in shallow-water wells above the upper boundary of the geothermal aquifer supports this vertical connection. The concept of regionally distinct, multiple geothermal aquifers, as proposed by Youngs and others (1980), is therefore believed to be unsubstantiated on the basis of water chemistry.

Although water temperatures also show an overall increase with depth, several interesting temperature anomalies were delineated. In particular, temperature regressions were noted at depths of 130 to 170 feet, 475 to 485 feet, and 620 to 625 feet in Arroyo #2, and at a depth of 325 to 515 feet in Moore #1. In addition, several other "hot water wells" (Fig. 28) display temperature reversals characteristic of shallow fault-charged hydrothermal systems (Benson and others, 1981). Initial temperature logging of CHS #1 also suggested the probability of a temperature reversal with depth. Maximum bottom-hole temperatures registered during the drilling of the five CDMG/CEC test holes, and the Roman Spa well was recorded in CHS #1 with a temperature of 190°F at a depth of 350 feet. Deeper drill holes show only minor increases in temperature with depth. Specifically, two test holes drilled at the Geysers to depths of 787 and 836 feet, and located at horizontal distances of 360 and 630 feet, respectively, from the Geysers well, recorded bottom-hole temperatures of 124°C and 118°C. Although the temperature logs of these holes show a continuous increase in temperature with depth, the lower maximum bottom-hole temperatures tend to indicate that the hotter water zone (135°C) must be confined and has little downward mobility. Moreover, a comparison of temperature logs

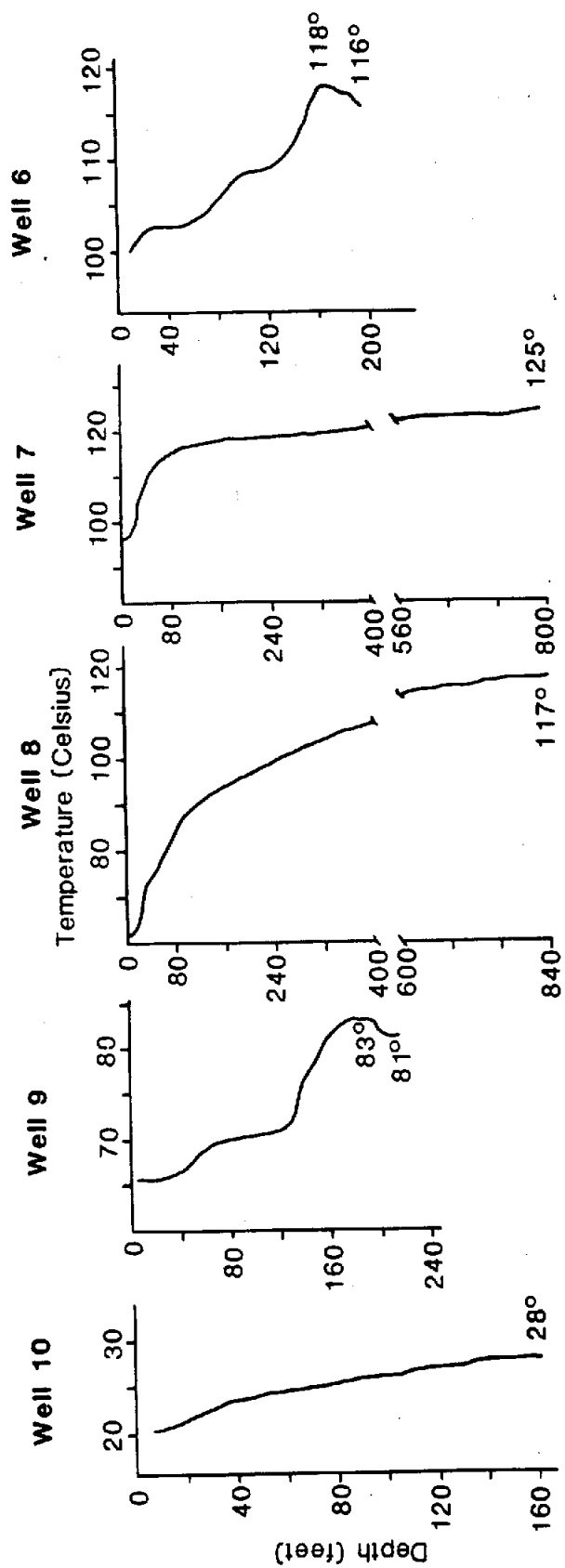


Figure 28. Temperature profiles for wells on line D-D'.

for all wells within the Calistoga Geothermal System Field indicates that maximum temperatures are reached at depths of approximately 200 feet below the surface. Wells deeper than 200 feet generally produce water at cooler temperatures (see for example Fig. 28). This is characteristic of lateral hot-water flow and conductive heat losses to the confining sedimentary layers (Bodvarsson and others, 1982).

#### C. STRATIGRAPHY AND STRUCTURE

The six lithologic logs depicted on Plate 1 show good stratigraphic correlation between adjacent holes. This correlation was made possible by the recovery of distinctive, uncontaminated samples via dual-tube drilling methods used in the drilling of four of the six test holes, Arroyo #1 and 2, Moore #1 and Calis #1.

The upper Napa Valley is a shallow basin underlain by a thick section of Quaternary alluvial sediments and Plio-Pleistocene pyroclastic deposits (Sonoma Volcanic rocks that dip 8° to 9° to the southwest). The lower units of the Sonoma Volcanic rocks are comprised of dacitic ash-flow tuffs that typically vary only in degree of induration. These ash-flow tuffs are intercalated with volcanic ash units of apparent air-fall origin and minor sedimentary facies of distally deposited volcanoclastic debris.

The upper dacitic ash-flow tuff is overlain by a thin sedimentary gravel unit that is correlative between the three westernmost drill holes. The gravel layer was in turn overlain by volcanic ash. The gravel horizon was interpreted by Taylor and others (1981) to represent a minor hiatus in volcanic activity allowing development of a brief depositional alluvial surface. The subsequent return to pyroclastic volcanic activity was again interrupted by a period of erosion marked by channel deposits intercalated with minor air-fall deposits of volcanic ash.

#### D. CONCLUSIONS

Exploratory well-drilling in Calistoga was conducted to provide information on subsurface conditions. Initial drilling by the CDMG determined that the depth of bedrock was deeper than originally believed as well as highly irregular. During this initial test drilling phase, Taylor (1981) had also suggested that the Calistoga field consisted of multiple aquifers, separated vertically by thin-to-thick lenses of clay. In a more recent test-drilling program, however, subsurface water chemistry data has shown that although clay layers are indeed present as a result of the complex alluvial history of the Napa Valley, they are not continuous and do not represent a major boundary subdividing the geothermal aquifer. In fact, there appears to be substantial mixing taking place, both between the freshwater aquifer and the geothermal aquifer, and within the geothermal aquifer itself.

The top geothermal aquifer, at an average depth of 200 feet, consists primarily of a zone of clay-to-silty gravel overlying a sequence welded tuff interbedded with dry-to-moist volcanic ash. The transition from cool meteoric water to geothermal fluid of high TDS and characteristic chemistry is gradual and occurs over a 100 foot interval. As is typical of fault-charged systems, a decline in temperatures with depth is common

in the Calistoga field when a well penetrates completely through the geothermal aquifer. Unfortunately insufficient data exists to determine if there is a corresponding change in water chemistry at this point. Although the subsurface stratigraphy is quite complex, due to the alluvial history of the Napa Valley, several easily recognized volcanic and alluvial units have been traced across the valley, providing a reasonable regional correlation. Further stratigraphic control and sample collection will, however, become available as additional wells in Calistoga are drilled.

## VII. MODEL OF THE CALISTOGA GEOTHERMAL RESOURCE

### A. INTRODUCTION

The Calistoga Geothermal field represents a shallow, moderate-temperature resource located at the head of the Napa Valley. It is similar to many near-surface low-to-moderate-temperature (<150°C) hydrothermal resources being developed in the Basin and Range and Cascades. The Calistoga resource, like many of these shallow thermal anomalies, is attributed to hydrothermal circulation. The Calistoga aquifer is believed to be associated with a central linear fracture system trending parallel to the axis of the Napa Valley and is characterized by a highly complex geological setting. Because of the shallow depth and moderate temperatures, the Calistoga geothermal system is very attractive for development of direct-use energy projects.

### B. DISCUSSION

Elements of a conceptual geothermal model must include a source of water, interconnected hydraulic conductivity, and a heat flux at the base of the system. Hydrothermal convective systems readily develop in areas where there is a residual heat supply related to relatively young volcanism. Located immediately southwest of the Clear Lake Volcanic field, which had activity into Holocene time, the Upper Napa Valley is bounded by and underlain by Tertiary pyroclastic deposits of the Sonoma Valley that range in age from 3.0 to 9.0 million years (Sarna-Wojcicki, 1976). However, field work for this study has mapped a thin layer of altered, volcanic ash on the northeast side of Calistoga near the Pachetau Spa. The age of the ash was determined by carbon-14 method to be approximately 5,000 years old, suggesting that the Upper Napa Valley may have been subjected to volcanic airfall deposits more recently than previously believed.

The heat source or "driving" mechanism for the hydrothermal convection system at Calistoga is thus probably the residual heat from the magma chamber or chambers that were the source of these late Pliocene-Recent (?) volcanic extrusives.

The primary requirement for a hydrothermal convection system, a fluid, is provided by meteoric water coming into contact with this residual heat source and then ascending along fault or fracture zones in the Calistoga vicinity. Waring (1915, p. 109) suggested that faulting was responsible for the hot water seepage at the original hot springs at Calistoga. Faye (1975) also inferred the existence of a fault aligned with the topographic axis of the Upper Napa Valley at Calistoga. Others have, at various times, speculated on the existence and location of faulting in the subsurface of the Upper Napa Valley. Geophysical studies conducted by Youngs and others (1980) indicated several areas of possible, but inconclusive, evidence of faulting associated with areas of known geothermal waters, and physical evidence developed during the CDMG/CEC drilling program tended to support this hypothesis.

The geochemical mapping of linear anomalies accomplished during this assessment program coupled with hydrologic and hydraulic data obtained

during this study substantiates the existence of a fault or fracture zone(s) located along the axis of the Napa Valley. Upwelling of geothermal fluids along this fault/fracture system (manifested at the surface by a rise in water levels in wells located along the fault/fracture zone) allows for the continuous supply of hot mineralized water to recharge the Calistoga reservoir. The location of the two areas with the hottest surficial waters, the California Geyser at 135°C, and Pacheteau's Spa at 121°C, are coincident with the projected traces of fault (see Fig. 18). Both of these areas produce water from drilled wells at shallow depths of 192 feet and 201 feet respectively.

### C. TEMPERATURE REVERSALS

Temperature reversals are typical of fault-charged systems found in many geothermal areas throughout the world. Examples of such systems in the western part of the United States are the high-temperature fields at Roosevelt Hot Springs, Utah, and East Mesa, California. Low-to moderate-temperature systems of this type include Klamath Falls, Vale, Oregon, and the Susanville hydrothermal system in California.

Figure 28 represents a series of six temperature gradient wells drilled by Occidental Geothermal Inc. perpendicular to the axis of the Napa Valley, on the west side of Calistoga. Wells 6 and 9 show reversal of temperature with depth. Youngs and others (1980), utilizing their recently obtained knowledge of subsurface characteristics, developed a conceptual model to explain the diagnostic profiles of each of the wells shown in Figure 28. Figure 29 is a schematic diagram of this model (after Youngs and others, 1980). A more analytical model has also been developed for fault-charged resources by Lawrence Berkeley Laboratory (LBL). Taking a mathematical approach, the LBL model calculates the temperature distribution of the system as a function of the flow rate into the aquifer, the temperature of the water entering the aquifer, the initial temperature profile, system geometry, rock properties, and time (Bodvarsson and others, 1981; Benson and others, 1981). The primary assumptions of the LBL model have been summarized by Benson and others (1981) and are listed below:

- (1) The mass flow is steady in the aquifer, horizontal conduction is neglected, and temperature is uniform in the vertical direction (thin aquifer). Thermal equilibrium between the fluid and the solids is instantaneous.
- (2) The rock matrix above and below the aquifer is impermeable. Horizontal conduction in the rock matrix is neglected.
- (3) The energy resistance at the contact between the aquifer and the rock matrix is negligible.
- (4) The thermal properties of the formations above and below the aquifer may be different, but all thermal parameters of the liquid and the rocks are constant.

In a schematic diagram of the LBL model shown in Figure 33, hot water starts to flow up the vertical fault at time  $t=0$ , and is recharged into a relatively thin horizontal aquifer under forced convection. The

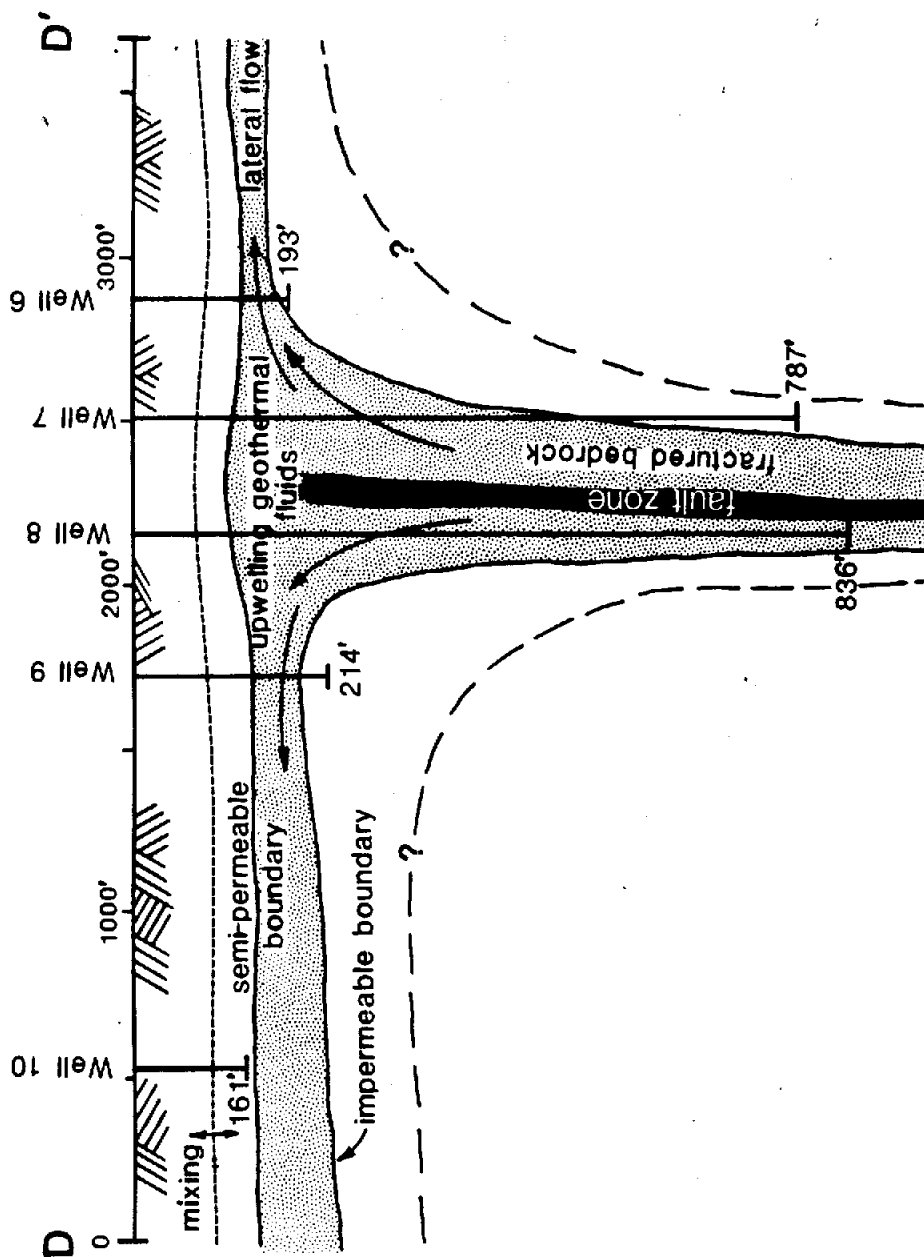


Figure 29. Schematic diagram of the fault-charged hydrothermal system at Calistoga. Water wells shown in Figure 28 are interpreted in terms of distance to the fault or fracture zone. (After Youngs and others, 1980.)

behavior of the system is then controlled by the above assumptions. Using this model, the evolution of a hypothetical system can be studied. In simple terms, Figure 30 can be envisioned as the evolution of a single temperature profile at any given location away from the fault. Before the initiation of hydrothermal circulation, the temperature profile is linear (normal geothermal gradient). When water begins to flow up the fault and into the aquifer, the aquifer begins heating. The fluid flows laterally in the aquifer, losing heat by conduction to the caprock and basement. A distinctive temperature reversal forms below the aquifer. With increasing time, conductive heat losses to the caprock stabilize and a typical linear conductive gradient is established. As time approaches infinity, the temperature below the aquifer stabilizes and becomes nearly constant with depth.

Utilizing this model, the temperature gradient profiles shown in Figure 28, and Plate 1, can all be explained in terms of distance away from the central fracture system, as shown in Figure 30.

Another application of this model is to calculate the rate of hot water recharge into an aquifer, given sufficient information about the areal and vertical temperature distribution in the aquifer. The model has been successfully applied to the Susanville, California resource, a low-temperature hydrothermal system located in the foothills of the Sierra Nevada (Benson and others, 1981). Data from more than 20 exploration and production wells were used to outline a thermal anomaly. Using the mathematical model, a recharge rate and recharge temperature were determined and applied to demonstrate an adequate resource for a minimum of 30 years. The model was further able to suggest methods of enhancing the exploitation of the reservoir to increase reservoir longevity. A similar analysis is currently being planned for the Calistoga Geothermal field.

#### D. PRODUCTION AND INJECTION WELL SITING

Location of a production well as close as possible to the central fault/fracture system will allow production of the hottest fluid; this will also optimize the stimulation of recharge from the fault and prevent overdraft of the resource, should an increase in production become desirable. Proper injection well-siting is critical in fault-charged systems because an inappropriately placed injection well can create premature cooling of the production well. Injection well-siting criteria are as follows:

- (1) Inject downstream from the production well, or at a sufficient depth below the level of production to prevent premature cooling.
- (2) Locate the injection well so that the pressure buildup due to injection does not negate the production-enhanced flow from the fault.
- (3) Minimize the steady-state interflow between the production and injection well. With proper siting, interflow between the wells may be negligible.

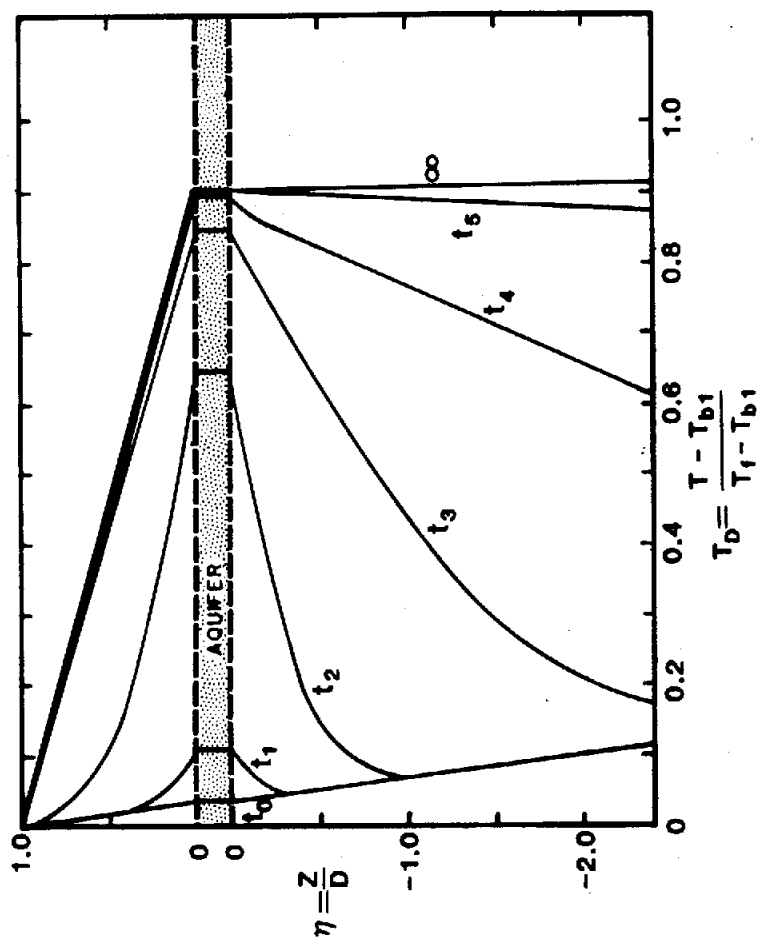


Figure 30. Evolution of a fault-charged hydrothermal system. (After Benson and others, 1980.)

## E. RESERVOIR VOLUME ANALYSIS

A geothermal reservoir is a complex, heterogeneous volume of rock and water, but most of the thermal energy is contained in the rock. Most volumetric estimates consider the reservoir a volume of rock and water regardless of permeability and porosity. That is, typically, no attempt is made to distinguish those parts of a reservoir that are permeable and porous from those that are not.

Figure 20 shows the location of 140 water wells located near Calistoga. All of these wells have temperatures greater than or equal to 25°C below a depth of 200 feet. An approximate boundary line enclosing the wells was drawn and then modified to fit geophysical and other evidence as appropriate. This boundary serves as an estimate of the lateral extent of the geothermal aquifer pending revisions based on future drill holes. The enclosed area is approximately 5.79 square miles.

Youngs and others (1981) vertically divided the upper Napa Valley into four subsurface zones. From top to bottom these are: (1) alluvial sediments from the surface down to 120 feet in depth, (2) alluvial sediments lying below 120 feet and extending to the top of the underlying southwest dipping pyroclastic beds, (3) impermeable pyroclastic material composed wholly of volcanic ash and ash-flow tuff and (4) saturated pyroclastic material and/or alluvial sediments underlying Zone 3.

Zone 1 - Based upon information collected during the Calistoga well canvass and the drilling program, the top 120 feet of alluvial sediments has been withdrawn from the geothermal reservoir assessment on the basis of water temperature. Although saturated, only very isolated wells produce waters in excess of 25°C from a depth of less than 120 feet in the Calistoga area.

Zone 2 - On the basis of geophysical work and the drilling program, the thickness of alluvium has been shown to progressively increase in a southwesterly direction at an assumed dip of approximately 9°. This dip has been projected to the western margin of the valley, with a resultant maximum section of approximately 1,400 feet of alluvial sediments. Thus, the average section for this prism yields an approximate volume of sediments 640 feet deep by the 5.79 square miles of area that probably contains interstitial waters with a temperature greater than 25°C. This gives a tentative mean reservoir thermal energy of  $0.52 \times 10^{18}$  Joules. Kunkel and Upson (1960) used specific-yield values that ranged from 5 to 8 percent to estimate the volume of water in the alluvial aquifer, and Faye (1974) used a specific-yield value of 6 percent for the alluvial aquifer. A hydrologic study in the Sonoma Valley by the Department of Water Resources utilized a specific-yield value of 6.95 percent (Herbst, 1981) for the alluvium. Because the alluvial section and the large data base used by DWR in the Sonoma study are similar to those of the Upper Napa Valley; a specific-yield factor of 6.95 percent was utilized for the Upper Napa Valley. Thus, using a specific-yield value of 6.95 percent and assuming peripheral vertical barriers, an estimate of the total quantity of geothermal water in storage in the upper alluvial aquifer of the Upper Napa Valley is 135,000 acre-feet. However, based upon the DWR Sonoma Study, perhaps only 10-15 percent of this water can realistically be withdrawn (Youngs and others, 1981).

This consideration reduces the upper aquifer yield of geothermal water to the range of 13,500 - 20,250 feet.

Zone 3 - Three of the drill holes shown on Plate 1 encountered a thick section of volcanic ash and ash flow tuffs that contained no interstitial water; these sections were impermeable barriers to vertical groundwater migration. This unit is considered to have limited storage capacity.

Zone 4 - The Arroyo #2, Moore #1, Roman Spa and GHS-1 drill holes were terminated in a dacitic ash flow tuff unit. Although the upper part of this unit appeared to be welded and virtually impermeable, the underlying scoriaceous material produced a large volume of hot water. As shown on the drill logs, a very rapid increase in temperature, in conjunction with a large volume of water, was produced upon penetration of the permeable scoriaceous volcanic material. Both of these physical parameters were unknown prior to the CDMG study and this underlying aquifer may represent a major addition to the geothermal resource in the Upper Napa Valley. Three major problems arise with trying to model this underlying aquifer: (1) the actual vertical thickness of this unit are unknown, for none of the drill holes hit Mesozoic basement rocks; (2) the actual hydrologic properties (that is permeability, hydraulic conductivity) of this underlying unit are unknown because the actual physical composition of the unit (whether alluvial sediments or pyroclastic debris flows) is unknown; and (3) the lateral extent to the West of this underlying aquifer basin is unknown.

The Arroyo #2 drill hole, which had a total depth of 885 feet, is the westernmost, "deep" (>600 feet) drill hole in the Upper Napa Valley area. As shown on Plate 1, this drill hole just barely penetrated into the saturated dacitic scoriaceous material, with a resultant increase in water. The gravity profile Figure 4 shows a thickening of sediments to the southwest, although the largest gravity anomaly is located well west of the currently projected structural discontinuity coincident with Highway 129. Thus, if the Zone 3 pyroclastic beds are continuous to the west and maintain a dip of 9°, the underlying Zone 4 geothermal water would be very deep at the western margin of the Valley. This fact could explain why geothermal waters have not been delineated in this area; wells simply have not been drilled to depths adequate to encounter the resource.

Zone 2 of Youngs and others (1982) is believed to represent the main body of the Calistoga reservoir. The average thickness of the aquifer in this zone has been estimated at 640 feet (Youngs and others, 1981), the main portion of the aquifer is probably no more than 100 feet as shown in Figure 30. This lower values stems from the fact that the aquifer thins to less than 100 feet near the zone of upwelling. Thus, the usable volume of the resource is probably substantially less, using volumetric calculations. A conservative, steady-state aquifer yield of approximately 13,500 - 20,250 acre feet or  $4.4 \times 10^9$  to  $6.6 \times 10^9$  gallons has been estimated from these volumetric calculations. Current withdrawal of water from the resource by bottlers and spa owner has been estimated at  $55 \times 10^6$  gallons per year. Assuming no recharge to the system the reservoir should be expected to last approximately 100

years. Even under these extreme conditions, the proposed municipal heating system, producing fluids at a rate of 180 gallons per minute, should have negligible effect on the resource.

Moreover, geochemical and hydrological analyses completed for this study have demonstrated conclusively that the resource is being charged along a central fault or fracture system. The rate of natural charge and the rate of downstream discharge (surplus water) currently leaving the system, however, cannot be accurately determined. Therefore, rate of reservoir depletion can only be determined through careful well monitoring and numerical modelling techniques. Detectable drawdown of the potentiometric surface, and seasonally-corrected declines of indicator ions such as chloride in selected wells, will serve as a measure of the rate of reservoir depletion.

Geochemical and hydrologic mapping of the Calistoga geothermal resource however suggests that at present the resource exists under near-equilibrium conditions. Figure 20 indicate a component of downstream discharge to the southeast along the northeastern margin of the valley. Such a downstream discharge implies that surplus thermal water is leaving the Calistoga area naturally. This is interpreted to indicate that more water is leaving Calistoga than is currently being used. Conversely, Figure 5 indicates that there are areas in town that are actually drawing down the potentiometric surface, presumably through excess use. The areas affected by this possible cone of depression are located along Washington Street, south of Lincoln. Careful well monitoring will be necessary to verify the accuracy of Figure 5 and the geothermal model of the Calistoga resource at this and other critical locations within the greater Calistoga area.

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## IX. APPENDIX A

### WELL DESCRIPTION

#### ARROYO #1

This site was located approximately 100 feet east of the Napa River on a farm road on the Arroyo property, a 37 acre Vineyard. Important considerations in selecting this site were: (1) the site was near the projected deepest part of the Upper Napa Valley basin and would provide a deep alluvial section before encountering Franciscan Basement; (2) the site was to the west of a major trend of known hot water wells and would provide lateral control in that direction for known hot water; and (3) it was expected that a hole having a depth of about 1,000 feet (a limit imposed by State Division of Oil and Gas restrictions) would provide a maximum amount of useful correlative information.

This was the first site drilled by the CDMG. Drilling commenced on December 18, 1980, with the drilling of 50 feet and the setting of 50 feet of 8 1/2 inch I.D. conductor pipe. This pipe was necessary due to the landowner's request and a regulatory stipulation from the California Division of Oil and Gas (CDOG) that a blow-out preventor be installed. This stipulation from CDOG was subsequently rescinded upon field inspection by DOG personnel of the dual-tube rig, and was not required for other drill holes. Unfortunately, this conductor pipe, in conjunction with a near surface standing water level, proved to be a detriment to completion of this hole. Each time a rod change was made, the conductor pipe would immediately fill with water; and, upon restart of drilling, large volumes of water would be blown out of the hole and onto the area around the rig. Because this water was suspected of having high boron content and because with the onset of the winter rains it would not be possible to control its flow on the surface, the hole was abandoned at a total depth of 205 feet on December 24, 1980.

#### ARROYO #2

This site is located upon the same piece of property as Arroyo #1 but was sited on firm ground adjacent to Grant Street. Arroyo #2 is 1,200 feet east of Arroyo #1 and was intended as a substitute after the premature abandonment of that site.

Drilling commenced on December 29, 1980. The hole was abandoned on January 23, 1981, at a depth of 885 feet. The drilling of this hole was very slow and time-consuming due to the continual plugging of the tools by very plastic clays (altered volcanic ash). The tools were plugged a total of seven times at respective depths of 242, 442, 445, 662, 742, 802, 863 feet. The hole was abandoned at 885 feet due to very rapid increase in rod torque which signaled certain rotational freeze-up of the drill pipe, had drilling been continued. A wealth of new and unexpected information was obtained from this hole.

#### MOORE #1

This site is located at 2150 Greenwood Avenue within a 5-acre parcel owned by Mr. Tex Moore. The site was adjacent to a traverse along which gravity, magnetic, and resistivity geophysical surveys had been performed. The hole was planned in order to provide stratigraphic control for the geophysical surveys and to provide a correlative section that could be used, in

conjunction with the Arroyo #2 geologic log, in an attempt to produce a geologic cross-section of the Upper Napa Valley.

Drilling commenced on January 27, 1981. The hole was abandoned on February 4, 1981, at a depth of 562 feet. The same problems encountered in drilling Arroyo #2 were also present in the Moore #1 hole; namely, the continual plugging of the tools by very plastic clay (altered volcanic ash). Unfortunately, termination of this hole, because of a funding shortfall, resulted in abandonment of the hole before it intersected Franciscan basement rocks. However, much useful information was obtained from this hole, particularly with respect to stratigraphy and probable attitude of beds and with regard to confirmation of geothermal resource projections.

#### CHS #1

CHS #1 is a geothermal production well drilled for the Calistoga Unified School District and located on a gravel pad directly behind Calistoga High School. The well is currently used in conjunction with a downhole heat exchanger to provide space heating and hot water to a portion of the band building. It is proposed that the DHE be removed and the well converted to an injection well for the school district. The well is currently lined with 8 1/2 inch I.D. steel casing down to 350 feet, with the casing perforated from the 270 foot depth to 330 feet. Ten-inch conductor casing was set from the surface down to 50 feet. Regulatory requirements from the DOG also stipulated that a blow-out preventor be installed during the drilling due to uncertainty of bottom-hole temperatures. Drilling was completed in July of 1983. It is currently anticipated that the injection well will receive fluids at a rate of 40 gpm. The perforated zone which will accept the fluids is characterized by non-welded volcanic tuff (see Plate 1). Water temperature reached a maximum of 190°F at a depth of 350 feet. The temperature gradient measured after drilling was completed suggests that a decrease in temperature would be encountered at a greater depth.

#### CALIS #1

This hole is located on the southwest side of the City of Calistoga, 200 feet north of the Napa River in Sec. 36, T.9N., R.6W. It was drilled as a test well by the CEC in June 1984 and located on level asphalt in the parking lot of the Community Center and Sharpsteen Museum. The test well was completed to a depth of 516 feet and cased with 6 1/2 inch I.D. steel casing from the surface down to 160 feet, with plastic tubing (3 1/2 inch I.D. PVC pipe) extending from the surface through the steel casing to 400 feet, the maximum depth which the casing could be set. The plastic tubing was perforated its entire length. Water temperature at the bottom of the hole (400 foot depth) determined during subsequent logging measurements, reached a maximum of 183.7°F. Although located less than 300 feet south of the Roman Spa well, no volcanic material was encountered in the hole during drilling. This was considered unusual since a non-welded volcanic tuff could be traced across the Napa Valley in the other test holes drilled. It is possible that CALIS #1 is located just south of a volcanic plateau, perhaps in a buried ancestral drainage of the Napa River. Alternatively, it has been suggested (Youngs, personal communication 1986) that a major northwest-trending fault located parallel to the Valley axis on the southwest side, separates and displaces the sedimentary/volcanic section located south of the fault downward, relative to the sedimentary/volcanic section located north of the

fault. This is an appealing suggestion from a hydrologic standpoint; yet there is no geochemical or geophysical evidence for the presence of such a structure. However, water wells located to the south of the Napa River contain cool, fresh water, with chemical analyses indicating a nongeothermal origin. CALIS 1, located immediately north of the river, contains water of a mixed origin, but with a definite thermal overprint. This marked change in well-water temperature is probably best explained by noting that the wells south of the river are all shallow, and thus have not been drilled to depths adequate to encounter the geothermal reservoir. Since the water chemistry of CALIS #1 also indicates that a substantial amount of mixing is taking place here, lower temperatures and chloride values should be anticipated. It is also possible that the present southwest boundary of the field is approximately coincident with the Napa River. Thus, wells drilled to the south of the river would have water chemistries indicative of freshwater.

The test hole, CALIS #1, was redrilled as a potential production/injection well for the City of Calistoga in December 1984. The existing 3 inch PVC casing was removed and a 24-inch hole was then opened to allow for the setting of 20-inch conductor casing down to a depth of 14 feet. The drilling of the remainder of the hole was accomplished using a 17 1/2 inch tricone rock bit down to a depth of 569 feet. Ten-and-three-quarter-inch casing was set to a depth of 548 feet. Slotted casing was set in two distinct sections, from 238 feet to 313 feet and from 448 feet to 548 feet, respectively. The remaining section from 548 feet to TD was left as an open hole, and gravel packed with 3/8-inch rounded pea gravel up to 228 feet. The well was cemented from 228 feet to the surface. It is interesting to note that contrary to the test holes drilled by the CDMG, no dry zones were encountered during the drilling of CALIS #1. All permeable zones produced large volumes of warm water, and even clay layers, separating zones of higher permeability sediments, were saturated.

#### ROMAN SPA WELL

The Roman Spa well was drilled in September of 1984 as an additional geothermal supply well for the Roman Spa Resort. The well was located in the parking lot behind the resort, about 400 feet northeast of CALIS #1. The well was drilled to a depth of 240 feet and reached bottom-hole temperature of 180°F. The subsurface lithology in the upper 170 feet of the well is quite similar to both CHS #1 and CALIS #1. Below 170 feet, however, a volcanic sequence consisting of alternating layers of an andesite-dacite welded tuff, glassy tuffaceous rocks, and unwelded ash was encountered which continues to the bottom of the hole. The volcanic sequence represents the Sonoma Volcanic basement rock underlying the upper Napa Valley; similar sequences are found in all test holes except CALIS #1.